

MARS SCIENCE LABORATORY POST-LANDING LOCATION ESTIMATION USING POST2 TRAJECTORY SIMULATION

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The Mars Science Laboratory (MSL) Curiosity rover landed safely on Mars August 5th, 2012 at 10:32 PDT, Earth Received Time. Immediately following touchdown confirmation, best estimates of position were calculated to assist in determining official MSL locations during entry, descent and landing (EDL). Additionally, estimated balance mass impact locations were provided and used to assess how predicted locations compared to actual locations. For MSL, the Program to Optimize Simulated Trajectories II (POST2) was the primary trajectory simulation tool used to predict and assess EDL performance from cruise stage separation through rover touchdown and descent stage impact. This POST2 simulation was used during MSL operations for EDL trajectory analyses in support of maneuver decisions and imaging MSL during EDL. This paper presents the simulation methodology used and results of pre/post-landing MSL location estimates and associated imagery from Mars Reconnaissance Orbiter's (MRO) High Resolution Imaging Science Experiment (HiRISE) camera. To generate these estimates, the MSL POST2 simulation nominal and Monte Carlo data, flight telemetry from onboard navigation, relay orbiter positions from MRO and Mars Odyssey and HiRISE generated digital elevation models (DEM) were utilized. A comparison of predicted rover and balance mass location estimations against actual locations are also presented.

INTRODUCTION

On August 5th, 2012 at 10:32 PDT, Earth Received Time (ERT), the Mars Science Laboratory (MSL) team successfully landed NASA's largest rover, Curiosity, at Gale Crater on the surface of Mars. Months prior to Curiosity's landing, a landing location working group (LLWG) was organized with the main objective to determine best estimates of touchdown position and MSL locations during entry, descent and landing (EDL) based on the information available at the time of landing. The secondary objective of the LLWG was to determine impact locations of masses separated from MSL during EDL. Determining strategies for calculating and providing best estimates of touchdown location and MSL locations during EDL were important in supporting the Mars Reconnaissance Orbiter's (MRO) High Resolution Imaging Science Experiment (HiRISE) and Context Camera (CTX) teams in official rover localization and MSL on-parachute acquisi-

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tion. Immediately after Curiosity's touchdown was confirmed, initial best estimates of rover touchdown location and MSL positions during EDL were provided and released. In the days and weeks following landing, these best estimates were refined based on availability of additional data during EDL, such as Mars Odyssey (ODY) real-time data products and navigation filter trajectory reconstruction, and were also used in the determination of impact locations of the separated balance masses. Moreover, these best estimate locations were used to assess how predicted locations from the Program to Optimize Simulated Trajectories II (POST2)¹ EDL performance simulation compared to actual locations. POST2 was the primary trajectory simulation tool used to predict and assess EDL performance for MSL from cruise stage separation through rover touchdown and descent stage impact.^{2,3} Data from the POST2 simulation was utilized, along with real-time data during EDL, relay orbiter positions from MRO and ODY and HiRISE generated digital elevation models (DEM), to calculate best estimate locations for MSL pre- and post-landing.

The focus of this paper is twofold. The primary focus is to detail the approach taken in calculating best estimates of MSL locations, utilizing the MSL POST2 simulation, and the best estimate initial and refined results of: 1) rover touchdown location, 2) MSL location during EDL within MRO HiRISE imagery, and 3) entry balance mass (EBM) impact locations and their comparison to official MSL locations determined by the EDL, landing location and surface science teams. The secondary focus of this paper is to compare these best estimate and actual locations to POST2 simulation predictions to assess accuracy of EDL modeling and performance for MSL. The scope of work presented in this paper does not include a detailed description of the MSL POST2 simulation or detailed description of Monte Carlo analyses of predicted EDL performance.

POST2 SIMULATION OVERVIEW

The POST2 end-to-end MSL EDL performance simulation^{2,3} leverages the versatility and heritage of POST2 and adds routines specific to the MSL mission. This simulation begins one minute following cruise stage separation, nine minutes prior to the nominal atmospheric entry interface, and ends with descent stage (DS) impact, following rover touchdown and execution of the flyaway maneuver. Major EDL events modeled in the simulation include turn to entry, propulsion system pressurization, hypersonic guided entry, supersonic parachute deploy and inflation, subsonic heatshield jettison, terminal descent sensor start, Mars lander engine (MLE) warm-up and powered descent initiation, powered approach, rover separation and bridle umbilical device (BUD) deployment, rover touchdown detection, and DS flyaway. Figure 1 is a diagram showing the various MSL EDL models integrated into the main POST2 simulation, such as flight software (FSW), aerodynamic database, and parachute model. The MSL EDL performance simulation was used to support operations using a Monte Carlo approach. This methodology involved simulating thousands of different initial conditions with random spacecraft and environmental perturbations, generating statistics, and evaluating trends and performance. These Monte Carlo runs were given an alphanumeric designation and tracked via configuration control process. For example, OD179 represents the 179th orbital determination (OD) conducted during cruise from Earth to Mars that was then mapped to the initial states to be used in the EDL Monte Carlo.

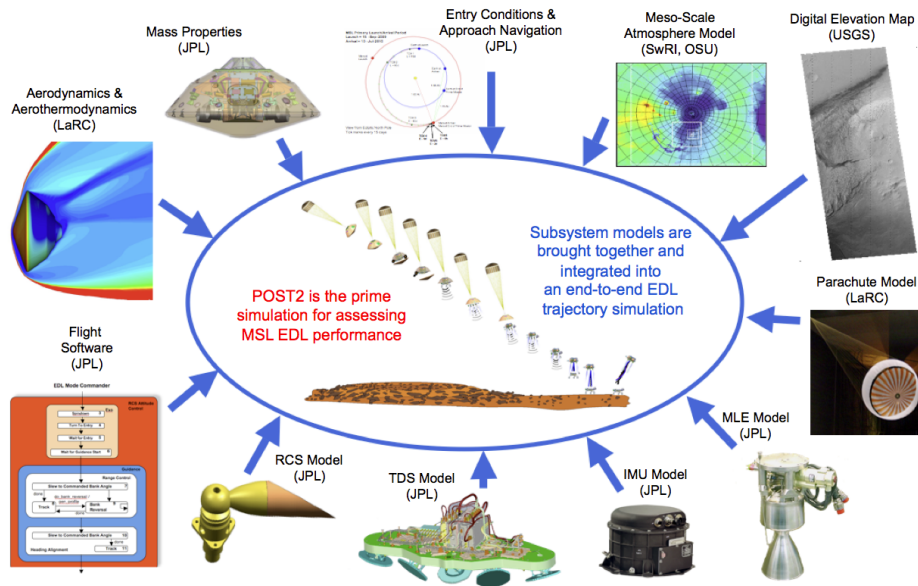


Figure 1. MSL EDL POST2 simulation modeling.

As the mission design life cycle progressed from conceptual design to operations, the fidelity of the various simulation models increased to reflect the maturity of the overall system design. Early in the design process, performance Monte Carlo runs were conducted in three degrees-of-freedom (3-DoF) with simplified models, allowing quick assessments of design trades. Later, the performance simulation was conducted in six degrees-of-freedom (6-DoF) and multiple bodies with the most detailed system models to verify required performance, in addition to evaluating the control system performance, sensor interactions, navigation error, parachute dynamics, detailed “Sky Crane” dynamics, tertiary impact locations (i.e. ballast mass impact location), footprint size, etc. The simulation also incorporated the MSL FSW used on the flight system to assess robustness under all study conditions. The use of FSW code allowed engineers to tailor operations support accordingly, as output was generated and reported the same way in simulation as was planned in flight. A common FSW output available during the real-time EDL sequence is known as an Event Record, or an EVR for short. Integration of the FSW provided a crucial test bed for understanding and using EVR’s during EDL for operational support.

TOUCHDOWN LOCATION

One of the main objectives of the LLWG was to determine best estimates of rover touchdown position based on the information available during and after the time of landing. This information was needed to assist the MRO HiRISE team in determining the official touchdown location of Curiosity after landing. Nominal and dispersed POST2 simulation predictions of touchdown location and the MSL-telemetered landing location estimate from the navigation filter were used to calculate the best estimate of rover touchdown latitude and longitude.

Simulation Predictions

POST2 nominal and dispersed trajectories were generated for each updated set of initial states available from the Navigation team.² These simulation predictions were used during MSL operations for EDL trajectory performance analyses in support of trajectory correction maneuver and parameter update decisions.² The latest Monte Carlo generated prior to atmospheric entry included a FSW parameter update conducted on July 30, 2012 (referred to as EPU1) and initial

states set from OD solution OD213, provided on the morning of August 5, 2012. Figure 2 shows the touchdown footprint from the OD213 8,000-case Monte Carlo. The green curve and diamond marker indicate the predicted 99-percentile landing ellipse of the Monte Carlo touchdown points and the center of that ellipse. The red “x” marker indicates the landing target latitude and longitude specified in the EPU1 FSW parameter file. The landing ellipse size is mostly determined by the dispersions included in the uncertainty modeling of the entry vehicle initial states, aerodynamics, Martian atmosphere, winds and initial attitude error. The typical predicted ellipse size of the touchdown footprint was about 19 x 6 km shown in Figure 2. For the OD213 Monte Carlo, the ellipse center miss-distance (the distance from the landing target to ellipse center) was 325 meters, within the desired range. The dispersed latitude and longitude data points from this Monte Carlo were used in the calculation of the uncertainty around the initial best estimate of rover touchdown location after landing.

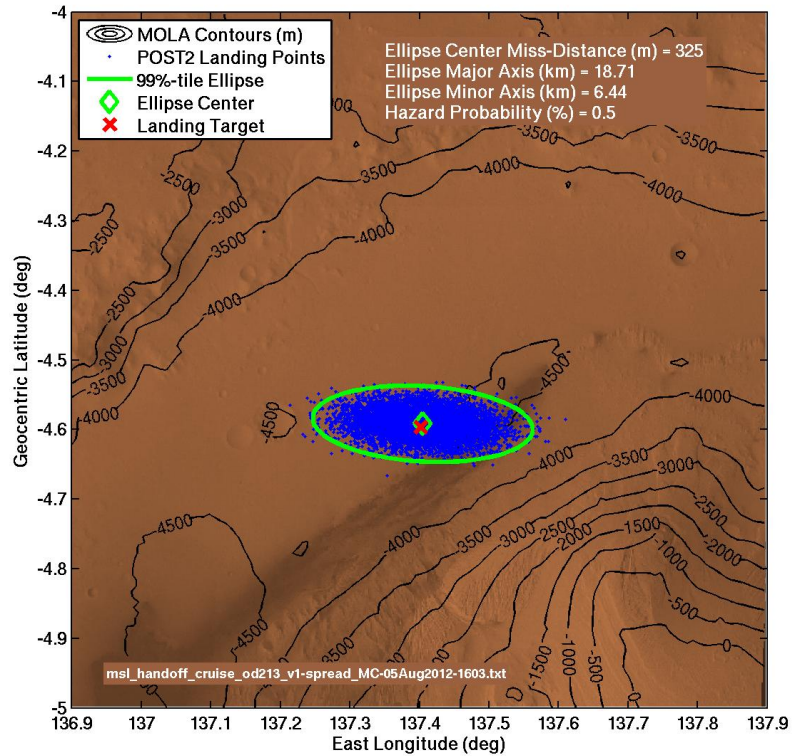


Figure 2. OD213 Monte Carlo touchdown footprint.

Initial Best Estimate Results

Immediately after rover touchdown was confirmed, the LLWG and EDL team provided an initial best estimate of the rover touchdown latitude and longitude and associated location uncertainties using the POST2 Monte Carlo data and EVR’s. Key navigated states from MSL-telemetered EVR’s were gathered during landing from ODY relayed data. This state was then transformed, as described below, to account for position, velocity and attitude navigation errors using the most current Monte Carlo results at the time of landing, OD213.

The touchdown location best estimate calculation required multiple steps and transformations, correcting first for the position navigation error or position knowledge error, and then correcting for velocity navigation error. The first step to determine the best estimate location was to capture the navigated position EVR in the landing target frame (LTF)⁴ at touchdown detected from MSL-

telemetered data, relayed by ODY during landing. The navigated LTF position was then converted to latitude and longitude. This latitude and longitude represented the touchdown point of the rover determined by the onboard navigation system, including all known and unknown errors at the time of landing (e.g., initial state per EPU1, initial attitude and gravity). The navigated LTF position was captured using Perl scripts which monitored all telemetered EVR's relayed during EDL and searched the appropriate EVR character string to print out the desired telemetry data. Figure 3 shows the EVR of the navigated LTF position used in the touchdown location best estimate calculation.

```
EDLGNC_EVR_TOUCHDOWN_DETECTED5:
At Touchdown:
Position_Ltf=
[2262.368089 277.134517 6.352356] m
```

Figure 3. Navigated LTF position at Touchdown Detected EVR.

After the onboard navigated latitude and longitude were determined, the next step in the touchdown estimate calculation was to determine the touchdown position knowledge error (defined as the difference in simulation truth and navigated position, converted to latitude and longitude at touchdown detected) from the most current POST2 nominal trajectory at the time of landing (OD227). This position knowledge error in touchdown latitude and longitude was then applied to the previously calculated onboard navigated latitude and longitude from the navigated LTF position EVR. Applying the touchdown position knowledge error to the onboard navigated touchdown location adjusted the onboard solution for sensor errors, biases and known position navigation errors. This estimate, adjusted using estimated position knowledge error, is known as the “first estimate”. From the latest Monte Carlo results generated at the time of landing (OD213), the 99-percentile ellipse of position knowledge error was then calculated to show the associated uncertainty around the first estimated touchdown point. This uncertainty ellipse represents the position, velocity, attitude, atmospheric and aerodynamic dispersions modeled in the Monte Carlo. To further reduce the uncertainty in touchdown estimate, corrections for navigated velocity errors (that stem from inertial attitude initialization error) were applied to the first touchdown estimate. By comparing the onboard navigated velocity vector to the first valid velocity measurement obtained from the terminal descent sensor (TDS), or the radar used during descent, the navigation filter was able to obtain a direct measurement of the velocity error in-flight, incurred during entry. This navigated velocity error was telemetered as the navigation filter converged velocity solution EVR and was used to account for the velocity error contribution to the touchdown position error. Figure 4 shows the navigated velocity solution EVR relayed during EDL, when the first TDS velocity measurements were processed.

```
EDLGNC EVR GNC NAV CONVERGED SOLUTION1:
NavFilter Converged With Vel
Solution = [-0.751962 0.011355 -0.163888] m/s
```

Figure 4. Navigated velocity error EVR.

Prior to entry, landing footprint errors obtained from the Monte Carlo analyses were used to determine the least-squares estimate of the transformation between the velocity error after navigation filter convergence and the touchdown position knowledge error. The product of the navigated velocity solution EVR and the least-squares estimate is applied to the first estimate in rover touchdown location. This new estimate, now accounting for the navigated velocity error, is known as the “second estimate”. This correction is possible because the velocity errors associated

with an initial attitude error are well understood and predictable, lying largely in a plane orthogonal to the entry velocity vector.⁵ The uncertainty in this second estimate was calculated as the error in the linear mapping between the velocity and position knowledge error, which remained consistent for each Monte Carlo. Because initial attitude error is one of the largest contributions to landing footprint size, applying this correction significantly reduces the uncertainty associated with the best estimate in touchdown location. Results from the POST2 simulations showed that the best estimated rover touchdown location, after applying both of the corrections above, was accurate to within 1 km.

Figure 5 shows the best estimate of the rover touchdown location determined at 10:38:50 PM PDT, less than seven minutes after touchdown was confirmed. The green diamond marker indicates the best estimate touchdown location and the predicted 99-percentile landing ellipse from Monte Carlo OD213 is shown in blue. This figure was approved for the media on landing night to inform the public of the initial best estimate of Curiosity's touchdown location, with the latitude and longitude at the top of the figure.

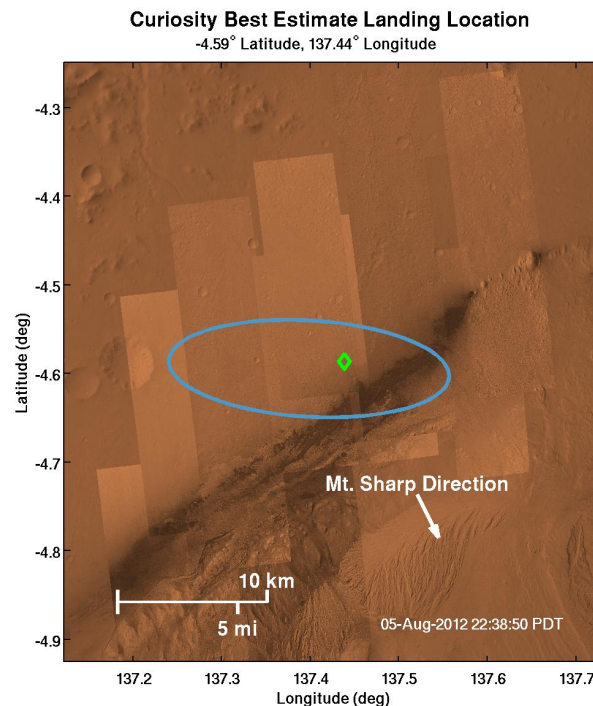


Figure 5. Initial best estimate of touchdown location provided to media.

Figure 6 shows a more detailed figure provided to the LLWG of the initial touchdown location best estimate and the location estimation uncertainties using Monte Carlo OD213. The left plot shows the predicted 99-percentile landing ellipse of 19 x 6 km. In addition, the on-board navigated touchdown point (black “+” marker) is shown, as well as the first and second estimates (green and red diamond marker, respectively). The actual official rover touchdown location (blue circle marker) determined later by the MRO HiRISE team was added to the plots afterward for comparison purposes. The right plot shows a zoomed in view of the touchdown locations, including the 6 x 3 km 99-percentile first estimate uncertainty ellipse indicated by the green curve and the reduced 1 km radius second estimate uncertainty indicated by the red curve. The predicted ellipse center of the Monte Carlo (OD213) and the landing target from EPU1 are also included in the plot as yellow “+” marker and magenta “x” marker, respectively. Determined at the time of

landing, the onboard navigated and estimated touchdown location were within 300 meters of each other, with the onboard estimated touchdown point well within the estimation uncertainty ellipses. The onboard navigated and actual rover locations were only 162 meters apart. This result shows the accuracy and performance of the navigation filter in determining rover touchdown location. In terms of predictions from Monte Carlo OD213, compared to actual rover location, the estimated to actual rover locations were no more than 250 meters apart and well within the 1 km second estimate uncertainty. The POST2 simulation, utilizing the onboard navigated LTF position and velocity error, performed very well in determining and estimating Curiosity’s landing location.

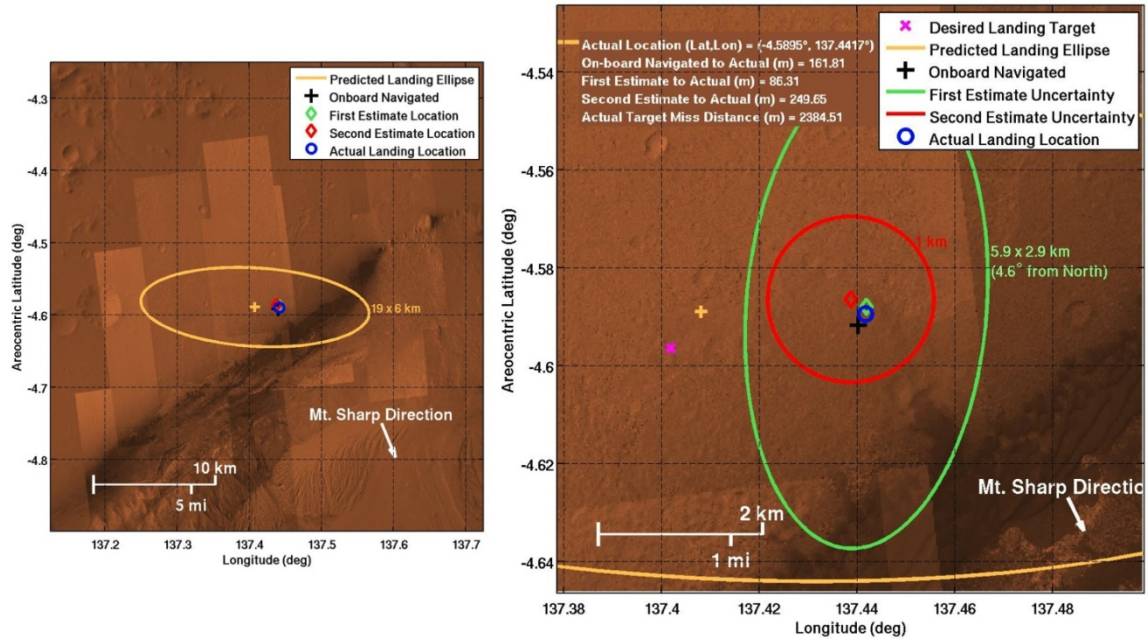


Figure 6. Rover touchdown location best estimate using OD213 Monte Carlo.

Refined Best Estimate Results

In the days following landing, refined estimates in touchdown location were made based on an update to the final, most accurate initial state set (OD230). A Monte Carlo was generated using the OD230 initial state set and the same process was followed to calculate a new best estimate of the rover touchdown location.

Figure 7 shows a plot of the refined touchdown location best estimate and the location estimation uncertainties using Monte Carlo OD230. The figure shows the touchdown locations, including the 99-percentile and 1-sigma first estimate uncertainty ellipse indicated by the green and green-dashed curve, respectively. The second estimation uncertainty is also shown as the red curve. The predicted ellipse center of the Monte Carlo (OD230) and the landing target from EPU1 are included in the plot as yellow “+” marker and magenta “x” marker, respectively. The onboard navigated and estimated touchdown locations are closer than the previous initial best estimate and less than 300 meters from each other. With the update to OD230, the estimated touchdown locations compared to the actual rover location within 224 meters. The POST2 simulation, utilizing the onboard navigated LTF position and the updated OD230 initial states, estimated Curiosity’s landing location over 20 meters closer than the initial best estimate results. Moreover, in comparison to the uncertainty around the estimated touchdown locations, the on-

board navigated and actual rover touchdown locations were well within the 1-sigma first estimate uncertainty ellipse and 1 km second estimate uncertainty.

Figure 8 also shows the revised best estimate touchdown location using OD230, as well as the 1-sigma predicted landing ellipse. The yellow dashed curve indicates the 1-sigma predicted landing ellipse from the OD230 Monte Carlo. When comparing the best estimate, onboard navigated and actual rover landing locations with the predicted landing ellipse, all touchdown points are well within the 1-sigma predicted landing ellipse. This result confirms accurate performance predictions and modeling of the POST2 simulation, as well as good performance of the navigation filter and EDL system.

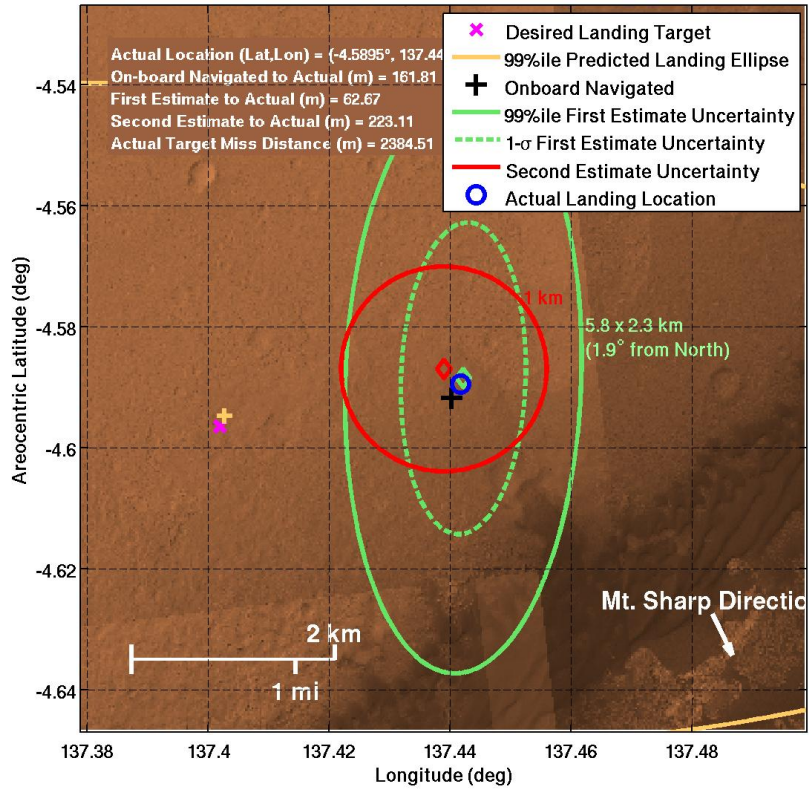


Figure 7. Rover touchdown location estimate update using OD230 Monte Carlo.

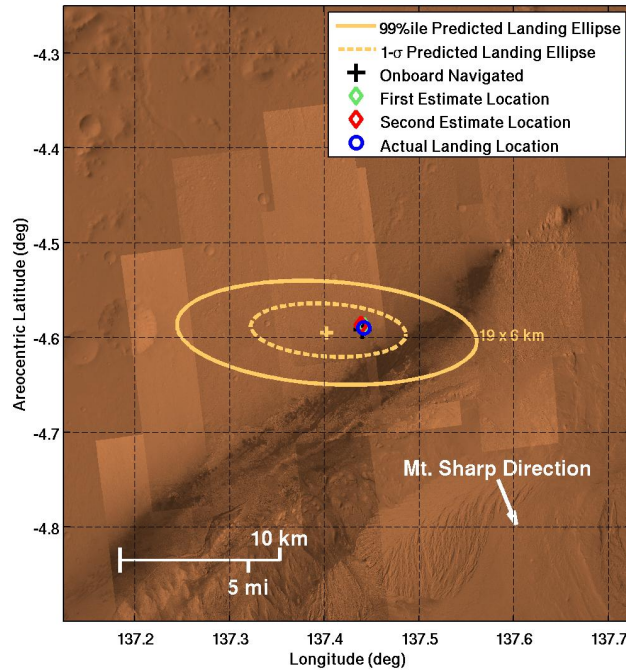


Figure 8. OD230 rover touchdown best estimate with 1-sigma landing ellipse.

MRO HIRISE IMAGE RECONSTRUCTION

The descent of MSL through the Martian atmosphere was covered by multiple orbiter relay and Earth-based assets. On MRO, HiRISE is a camera directed along MRO's spacecraft +Z axis that can be utilized to capture imagery from orbit. There are many reasons for MRO to acquire an image of MSL during its descent: trajectory location⁶, fault investigations, public outreach, etc. The process of designing the MRO profile used to capture the image of MSL was a cooperative effort between the MRO operations team, the MSL navigation team, and MSL EDL team. The following section will detail the process used, preliminary results, in-flight estimates, and final results of the HiRISE image acquisition as supported by the MSL EDL team and LLWG.

The imaging sequence utilized by HiRISE is known as a pushbroom acquisition, where the camera is turned on at a specified time, acquires imagery while the spacecraft follows the designed trajectory, and turns off once the image capture is complete. That is, the final image is a mosaic of images taken over a period of time. The HiRISE camera specifications include a red and color charge-coupled device (CCD). The red CCD width is 1.14 degrees wide (~6 km wide along the ground from MRO nadir at 300 km altitude⁷), and the color CCD width is 0.23 degrees wide (~1.2 km wide). That is a five times greater image area for the red CCD versus the color CCD. The CCD height is 0.18 degrees, with the final mosaic consisting of multiple 1.14 x 0.18 degree images. Efforts were made to ensure the acquisition of MSL inside the color CCD by utilizing Monte Carlo analysis from the EDL team to estimate the mean and dispersed MSL trajectories around which the MRO pointing profile would be designed.

MRO Attitude Profile Design for HiRISE Acquisition of MSL

The MSL Navigation team provided mean trajectories to the MRO operations team that were utilized to target the pointing profile. The EDL team provided 12 dispersed trajectories to the MRO operations team that represented the MSL trajectory bounds in downrange and crossrange to the landing target (short, long, left and right) and touchdown times that were early, nominal,

and late. To select the cases from an 8,000 case Monte Carlo run, the three variables of interest (downrange, crossrange and time) were normalized to be in the range of -1 to 1 with the mean at zero. The case closest to the parameters desired was selected. For example, for the nominal touchdown time that is short, downrange at touchdown is desired to be 1, crossrange at touchdown is desired to be zero and time at touchdown is desired to be zero. The Monte Carlo results were differenced from the downrange/crossrange/time targets and the minimum from the root-sum-squared of the three was the case selected. The results are shown in Table 1, which were taken from the OD063 Monte Carlo prediction, made on February 14, 2012. The results were utilized by the MRO operations team to aid in designing the attitude profile for HiRISE image acquisition.

Table 1. OD063 POST2 Bounding Cases for MRO HiRISE Imaging Design

| | Downrange, km | Crossrange, km | Time Past EI, sec |
|---------------------------------------|----------------------------------|----------------------------------|--------------------------------------|
| Nom: Short / Long / Left / Right | 14.02 / -12.22 / -2.1 / -1.1 | 0.37 / -0.23 / -5.4 / 5.91 | 968.2 / 972.6 / 985.3 / 973.0 |
| Early: Short / Long / Left / Right | 8.12 / -8.35 / 0.76 / -0.62 | 0.24 / -0.65 / -3.89 / 4.68 | 905.9 / 924.6 / 916.3 / 920.8 |
| Late: Short / Long / Left / Right | 10.169 / -8.99 / 1.66 / -2.92 | -1.774 / -1.40 / -4.08 / 4.72 | 1043.8 / 1041.8 / 1040.8 / 1035.8 |

Probability of HiRISE Acquisition of MSL

As MSL approached Mars, improved estimation of the spacecraft state and measurement errors allowed greater accuracy in trajectory determination. The MSL Navigation team provided mean trajectories to the MRO operations team who then provided a new state and attitude estimate for evaluation of HiRISE acquisition. At TCM-4, which occurred on July 30, 2012 the HiRISE acquisition predictions were made from the POST2 Monte Carlo OD179. Acquisition was assumed when MSL was within the half angles of the tiled vertical and horizontal fields of view. To calculate the angle between MSL and the MRO HiRISE look direction, three quantities must be known.

1. MSL position
2. Start/Stop time of HiRISE image acquisition
3. MRO position/orientation

The position of MSL was determined from the POST2 simulation, reported in the J2000 frame relative to Mars. The start and stop times of the image acquisition, were estimated to start at 05:16:20.340 UTC and stop 43 seconds later. The position and orientation of MRO, was determined from predicts provided by the MRO operations team in the J2000 frame relative to Mars. The look direction of the HiRISE camera was directed along the MRO spacecraft +Z axis with the side direction measured along the +Y axis. The dot product of the MRO to MSL vector was taken with the HiRISE up and side vectors to project the distance along the respective vertical and horizontal directions. Using the vertical and horizontal distances to MSL from the HiRISE look direction, the vertical and horizontal angles could be determined. The angles could then be compared against the HiRISE field of view to determine acquisition. The exact time of acquisition was assumed when the vertical distance was zero and the horizontal angle was less than the half angle of the HiRISE red CCD (0.57 degrees). Results of the OD179 analysis are shown in Table 2.

With probability of acquisition quantified, the operational aspect of locating MSL in the HiRISE image had to be addressed. Within the LLWG, a handoff was identified between the EDL team and HiRISE team where a prediction of MSL's location at the time of image acquisition would be provided. The handoff would make use of the real-time EVR data from MSL as relayed by ODY. Since the real-time data products that contained the state of MSL at 8 Hz intervals would take time to be fully processed, the state was interpolated between the received EVR's at parachute deploy, heatshield separation, MLE priming, backshell separation, and touchdown. By utilizing the EVR's, the handoff turnaround time was reduced to minutes instead of hours.

Table 2. OD179 Percent Cases Acquired in HiRISE Image.

| | |
|--------------------------|--------|
| MSL Acquired in Image | 74.28% |
| MSL in Parachute Descent | 54.69% |
| MSL in Powered Descent | 19.45% |
| MSL in Skycrane | 0.137% |

Operations Support for Preliminary Estimation of HiRISE Image

The handoff would be a simulated image of the HiRISE acquisition, requiring knowledge of four quantities:

1. IAU Mars Relative MSL position/orientation
2. IAU Mars Relative MRO position/orientation
3. Gale Crater digital elevation model for background map tie
4. MSL/parachute geometry

The MSL state data was provided by the FSW EVR's in real-time during landing and transformed to the IAU Mars Mean Equator and Prime Meridian frame⁴. The MRO state data was provided as predictions by the MRO operations team one day prior to atmospheric entry and orientation data as predictions from six days prior to atmospheric entry. Randy Kirk at USGS provided the Gale Crater DEM on April 4, 2012, and Fred Calef at JPL provided imagery as a stereo-imaged mosaic of CTX and HiRISE camera measurements. The MSL capsule was plotted using a symmetric 4.5 meter diameter, 70 degree sphere cone MSL geometry, oriented as reported from the EVR. The MSL parachute geometry was plotted according to size parameters given by Juan Cruz⁸, and oriented along the MSL axis of symmetry. The image was plotted in a MATLAB perspective projection as a mosaic of 1.14 x 0.18 degree images taken from the view of MRO to simulate the pushbroom acquisition method described above. In Figure 9, the image prediction is shown on the left, with the real HiRISE mosaic shown on the right. The vertical axis represents the time passed from the beginning of image acquisition.

The full mosaic is too large to allow visual identification of the MSL parachute, but gives an overview of the larger HiRISE image with respect to important trajectory parameters. In the simulated image on the left in the figure,

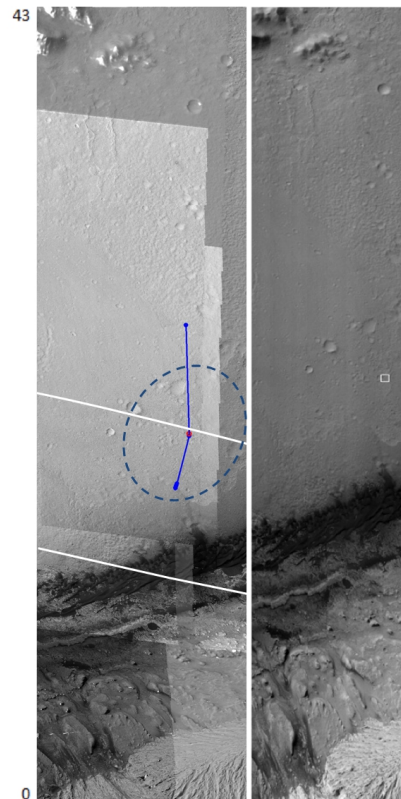


Figure 9. Simulated vs. real HiRISE overview image (HiRISE image credit: NASA/JPL-Caltech/UA).

the white solid line is the estimated

99-percentile landing footprint from the OD179 Monte Carlo, the solid blue line is the interpolated trajectory from the EVR's, the blue markers are the events reported by the EVR's and the dashed blue outline is the expected navigation error from the OD179 Monte Carlo mapped to the expected acquisition point (the same navigation error used in the touchdown location estimation). The expected time of acquisition was determined from the interpolated state to be 05:16:42.8 UTC. In the real image on the right, the white rectangular outline is the location where MSL was found in the image. From comparing the two images, the background map tie of the DEM makes the determination of MSL location in the real image much easier, as seen by the relative location of background craters. The simulated image is seen to provide a fast and efficient method of relaying EDL data to the MRO HiRISE team in an operational manner.

Refined HiRISE Image Results

The largest difference between the two images is the shift in the vertical placement. This shift is most likely due to the following error sources: MRO position error, MRO pointing error, HiRISE image start/stop time and MSL position error. As reconstruction efforts have proceeded, reconstructions of the above error sources have been refined. Scott Francis at Lockheed Martin provided the MRO position and pointing reconstruction. The HiRISE image start time was provided by Anjani Polit, University of Arizona, as 05:16:19.482 UTC, or approximately 1 second earlier than expected. The MSL position reconstruction was provided by Fred Serrichio at JPL. The reconstructed image using the updated datasets is shown in **Error! Reference source not found.** as a zoom-in of the MSL location. The blue diamond is the updated reconstruction location while the red circle is the initial estimate. The distance between the two estimates is 1.33 km relative to the locations HiRISE would have imaged MSL. The comparison between the two images of MSL relative to the background map-tie is shown to be very good, indicating confidence in the reconstructions.

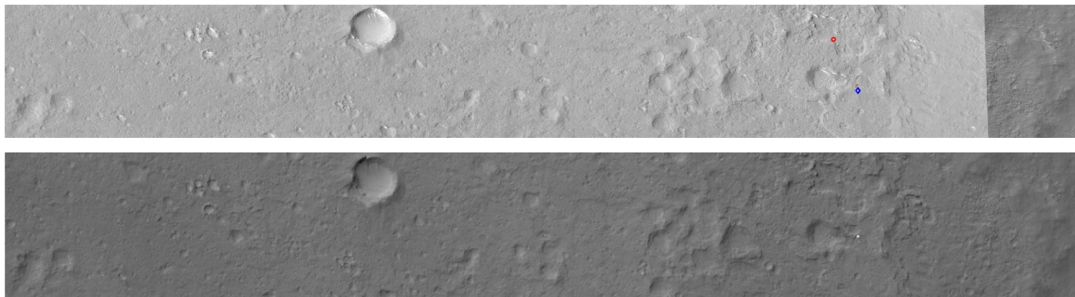


Figure 10. Zoom-in of MSL location (HiRISE image credit: NASA/JPL-Caltech/UA).

The reconstructed HiRISE image of MSL determined that MRO captured MSL approximately 2.669 seconds prior to the initial pressurization of the Mars Lander Engines used in powered descent, denoted as PV-5. At this phase in the EDL timeline, the heatshield would have been jettisoned from MSL for 78.08 seconds. The returned video frames of the Mars Descent Imager (MARDI) determined that heatshield impact was approximately 79 seconds after heatshield separation. Using the POST2 nominal heatshield trajectory, an estimated heatshield trajectory was evaluated for HiRISE acquisition that was coincident in location and time with the impact location of the heatshield and the reconstructed location of the heatshield at the time of jettison. The acquisition of the heatshield in the simulated HiRISE image was determined to be 4.869 seconds prior to heatshield impact. The simulated location of the heatshield is shown in Figure 11 on the left, highlighted by the blue diamond while the HiRISE image of the heatshield location is shown on the right, highlighted by the white square. The difference in location is likely due to the lack of a full heatshield trajectory reconstruction.

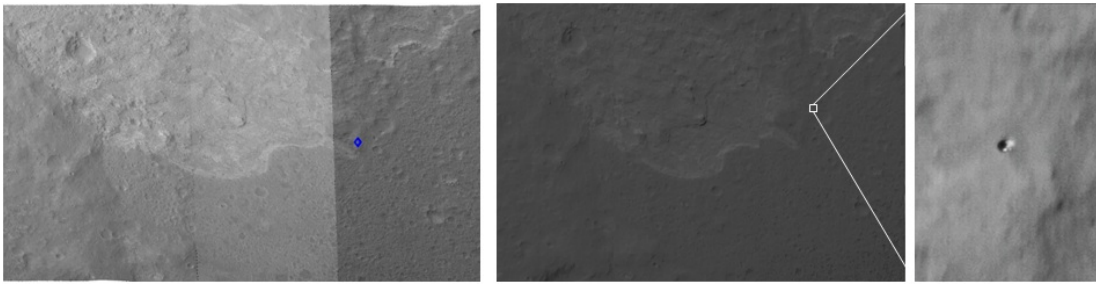


Figure 11. Zoom-in of heatshield location (HiRISE image credit: NASA/JPL-Caltech/UA).

The process of acquiring the HiRISE image of MSL during the descent to Gale crater was a multi-team effort that ended with a spectacular success. The ability to predict the location and uncertainty of MSL at various times during the EDL sequence helped to aid the design teams that planned the MRO HiRISE acquisition. The final image, as seen in Figure **Error! Reference source not found.**, indicates that the image acquisition occurred according to plan, as the two images show the expected parachute configuration of MSL with the simulated image on the left and the actual image during flight on the right. Future use of imaging during EDL phases can utilize the process described here to help better refine the image acquisition desired.

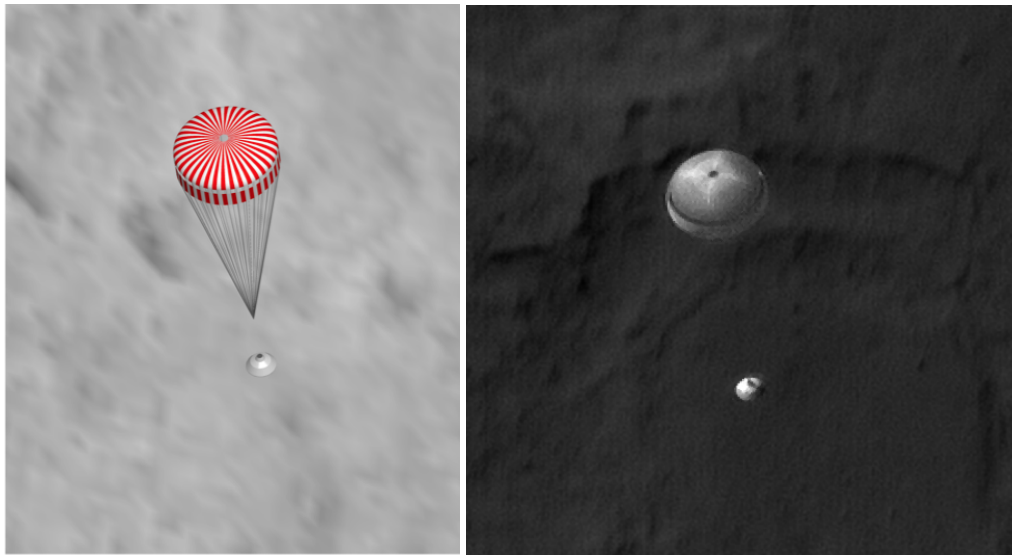


Figure 12. Simulated vs. real HiRISE image of MSL (HiRISE image credit: NASA/JPL-Caltech/UA).

ENTRY BALANCE MASS LOCATION

In the days following rover touchdown confirmation, the MSL EDL team, MRO CTX team and LLWG began to determine the impact locations of the masses separated from MSL during EDL. The assessment of the separated mass impact locations was the secondary objective of the LLWG. The POST2 simulation was used to generate the predicted impact points of the separated EBM's, which were also provided to the MRO CTX team to aid in the localization of the impact points on the Martian surface.

The EBM impact location predictions were obtained by isolating a case from the OD230 POST2 Monte Carlo based on the times of the EBM jettisons (or pyrotechnic firings) from the time point data, as well as the navigated planet-relative velocity EVR at the start of the EBM jettisons, relayed by ODY during EDL. A 1-sigma uncertainty in impact location, determined by the

OD230 Monte Carlo, was applied around the EBM impact location predictions. Figure 13 shows the EBM impact point predictions, indicated by the dark blue circle markers, and the associated 1-sigma EBM impact prediction ellipse. Overlaid on the plot is the HiRISE imagery of the actual EBM impact locations (marked by black vertical arrows), localized after landing by the MRO CTX team. The figure also shows the actual rover touchdown location as the red “x” marker and 99-percentile predicted landing ellipse for reference. The balance mass impact location predictions shown in the figure, when compared with the actual impact locations determined by the CTX team, had a similar impact pattern and placement. Also, they were within the 1-sigma expected uncertainty from the OD230 Monte Carlo. This result shows good performance predictions and modeling of the EBM’s in the MSL EDL simulation.

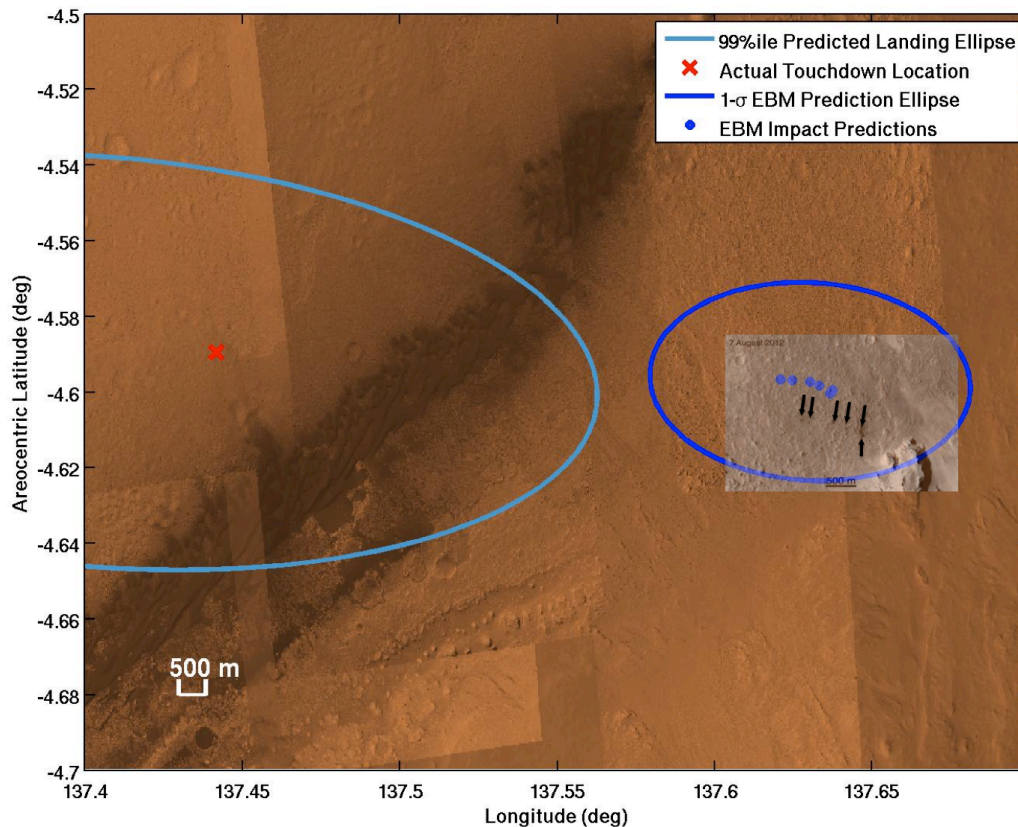


Figure 13. EBM predictions from OD230 Monte Carlo (Inset image credit: NASA/JPL-Caltech/MSSS).

CONCLUSION

The approaches taken in calculating best estimates of MSL locations during EDL, utilizing the MSL POST2 simulation, have been discussed. The best estimate initial and refined results of: 1) rover touchdown location, 2) MSL location during EDL within MRO HiRISE imagery, and 3) EBM impact locations and their comparison to official MSL locations determined by the EDL, landing location and surface science teams have also been presented. The POST2 simulation, utilizing the onboard navigated LTF position and velocity error, performed very well in aiding the determination and estimation of Curiosity’s landing location. The rover touchdown best estimate, onboard navigated and actual rover landing location, were all within the 1 km and 1-sigma predicted uncertainty. This result shows good performance predictions and modeling of the POST2

simulation, as well as good performance of the navigation filter and EDL system. The process of acquiring the HiRISE image of MSL during its descent was a successful multi-team effort, which produced the ability to predict the location and uncertainty of MSL at various times during the EDL sequence to aid in the MRO HiRISE acquisition. The process described may be utilized to help future imaging during EDL phases and to refine the image acquisition desired. The balance mass impact location predictions, when compared with the actual impact locations determined by the CTX team, were within the 1-sigma expected uncertainty. This also shows good performance predictions and modeling of the EBM's in the MSL EDL simulation.

Future work includes the assessment of MSL POST2 simulation predictions of the parachute-backshell and heatshield surface impact points with the actual locations determined by the MRO HiRISE and CTX teams. The comparison of cruise stage balance mass (CBM) impact location predictions with actual locations will not be assessed due to the overlap and indistinguishable nature of the CBM impacts and cruise stage debris on the Martian surface.

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REFERENCES

- ¹ Striepe, S.A., et al, "Program to Optimize Simulated Trajectories (POSTII), Vol. II Utilization Manual," Version 1.1.6.G, January 2004, NASA Langley Research Center, Hampton, VA.
- ² Way, D.W., Davis, J.L., and Shidner, J.D., "Assessment of the Mars Science Laboratory Entry, Descent, and Landing Simulation", AAS 13-333, *AAS Space Flight Mechanics Meeting*, Kauai, HI, February 2013.
- ³ Striepe, S.A., Way, D.W., et al, "Mars Science Laboratory Simulations for Entry, Descent and Landing," Vol. 43, No. 2, pg. 311-323, *Journal of Spacecraft and Rockets*, March-April 2006.
- ⁴ P. Burkhart, "MSL Update to Mars Coordinate Frame Definitions" JPL Interoffice Memorandum, 343B-2006-004, Pasadena, CA, 2006 (unpublished).
- ⁵ Kipp, D., San Martin, M., Essmiller, J., and Way, D.W., "Mars Science Laboratory Entry, Descent and Landing Triggers", IEEE-2007-1445, *IEEE Aerospace Conference*, Big Sky, MT, March 2007.
- ⁶ Wells, G., Dutta, S., Mattson, S., Lisano, M., "Phoenix Location Determination Using HiRISE Imagery", IPPW-7-340, *Interplanetary Probe Workshop (IPPW)-7 Barcelona*, Spain, June 2010.
- ⁷ J. Bergstrom, W. Delamere, A. McEwen, "MRO High Resolution Imaging Science Experiment (HiRISE): Instrument Test, Calibration and Operating Constraints," *International Astronautical Federation - 55th International Astronautical Congress 2004*, Vol. 9, pp. 6210-6216, 2004.
- ⁸ Cruz, J. R., et al, "Parachute Models Used in the Mars Science Laboratory Entry, Descent and Landing Simulation", *22nd Aerodynamic Decelerator Systems Conference*, Daytona Beach, FL, March 2013 (unpublished).