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POWERED FLIGHT DESIGN AND RECONSTRUCTED PERFORMANCE SUMMARY FOR THE MARS SCIENCE LABORATORY MISSION

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The Powered Flight segment of Mars Science Laboratory's (MSL) Entry, Descent, and Landing (EDL) system extends from backshell separation through landing. This segment is responsible for removing the final 0.1% of the kinetic energy dissipated during EDL and culminating with the successful touchdown of the rover on the surface of Mars. Many challenges exist in the Powered Flight segment: extraction of Powered Descent Vehicle from the backshell, performing a 300m divert maneuver to avoid the backshell and parachute, slowing the descent from 85 m/s to 0.75 m/s and successfully lowering the rover on a 7.5m bridle beneath the rocket-powered Descent Stage and gently placing it on the surface using the Sky Crane Maneuver. Finally, the nearly-spent Descent Stage must execute a Flyaway maneuver to ensure surface impact a safe distance from the Rover. This paper provides an overview of the powered flight design, key features, and event timeline. It also summarizes Curiosity's as flown performance on the night of August 5th as reconstructed by the flight team.

INTRODUCTION

Upon entering the atmosphere of mars, the MSL capsule is traveling at a velocity of almost 6 km/s. It is the job of the Entry, Descent, and Landing (EDL) system to bring that velocity to 0.75 m/s within what has become known as The Seven Minutes of Terror[‡‡]. An overview of the EDL sequence is shown in Figure 1 and a more detailed description of the overall EDL architecture can be found in Steltzner, et al.[1] and Prakash, et al.[2] Although there is still detailed analysis ongoing,

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[‡‡] http://www.jpl.nasa.gov/video/index.php?id=1090

this paper will summarize the overall Powered Flight design and show comparisons between the pre-flight predictions and the in-flight performance.

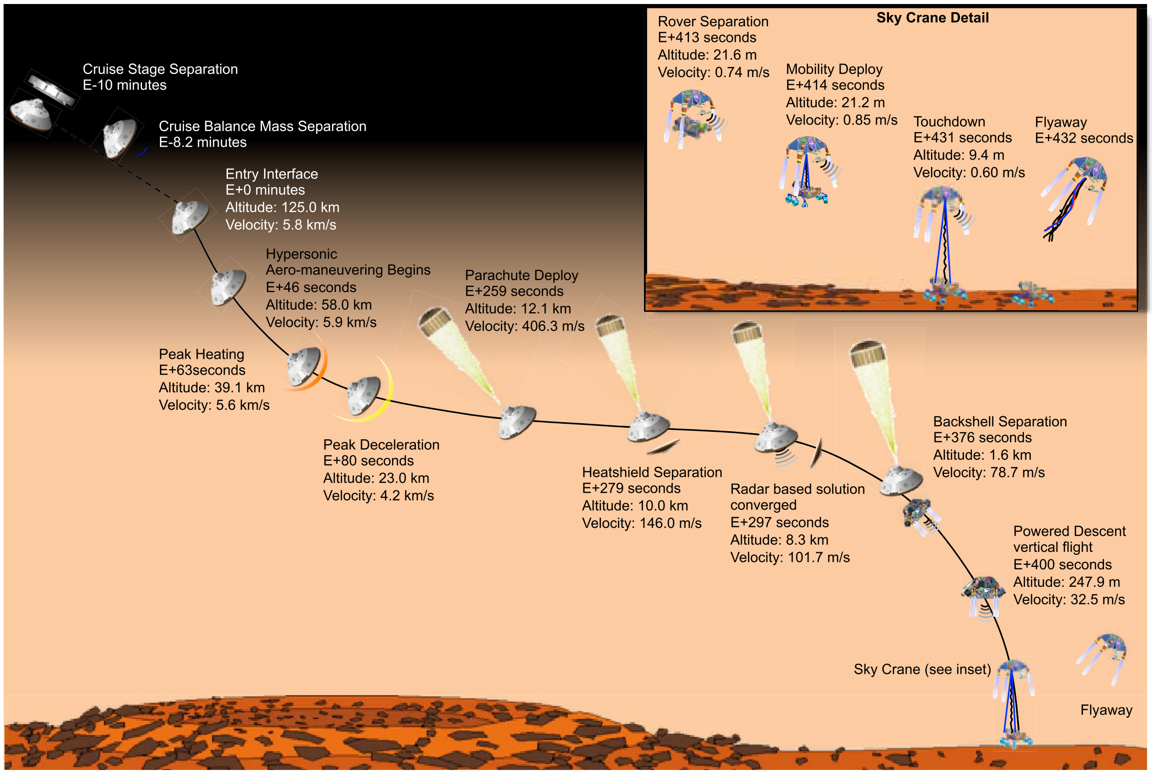

Figure 1. Mars Science Laboratory Entry Descent and Landing Sequence (Values shown are as-flown or reconstructed from flight data)

The Powered Flight segment of EDL begins at backshell separation (refer to Figure 1) and continues through the remainder of the landing sequence. Powered Flight refers to the use rocket engine power via the Mars Lander Engines (MLE) as the means of control throughout this phase of EDL.

POWERED FLIGHT DESIGN

Preparation for Powered Flight: Parachute Descent

Once the Entry Phase is complete and the capsule has slowed to approximately Mach 1.7 (~400 m/s) from atmospheric drag, the parachute is deployed and the heatshield is dropped allowing the Terminal Descent Sensor (TDS) – a 6 antenna, narrow-beam radar developed by JPL for this mission[3]– to have a clear line of sight to the surface. The TDS makes ground-relative velocity and altitude measurements which are combined with measurements from the Inertial Measurement Unit (IMU) in the on-board Navigation Filter software to produce estimates of the spacecraft position and velocity throughout EDL.[4] MSL in its on-parachute configuration is shown in Figure 2 – visible in the figure is the underside of the rover inside the backshell. The TDS is visible to the left side of the rover chassis.

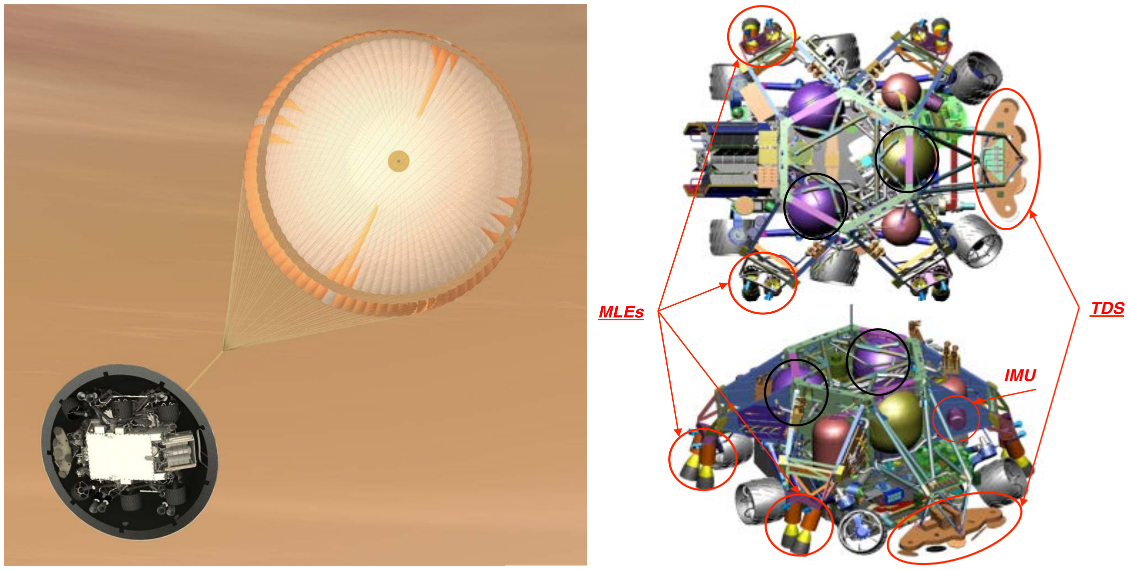

Figure 2. MSL Descending on the Parachute (Left, Image Credit: NASA/JPL-Caltech) and Location of the Terminal Descent Sensor and the Mars Lander Engines

Prior to use of the TDS, the position and velocity of the spacecraft was based solely on dead-reckoning from the IMU measurements. Once enough altitude and velocity measurements from the TDS have been taken, the Navigation Filter converges on a ground relative altitude and velocity. The Navigation Filter provides this velocity and altitude estimate to the Powered Descent controller for the remainder of EDL[5].

At an Altitude of 3000 m, pyrovalves in the propulsion system are opened to allow hydrazine to flow through a venturi and slowly fill the propulsion lines to the eight MLEs thereby avoiding rupture or damage from water hammer effects. This operation is referred to as priming the propulsion system. Since it takes approximately 7 s for the hydrazine to fill the entire volume of propulsion system lines, it is a requirement on the design that there be at least 8 s between the start of priming and the need to use the MLEs. First use of the MLEs occurs 1s after Backshell Separation (BSS).

Backshell Separation

Once the MLEs are primed, the Powered Descent start logic is enabled. As the spacecraft descends through the atmosphere toward the surface, the 8 Hz control loop constantly predicts the altitude of the spacecraft at the next timestep. It takes into account the current vertical descent rate, the amount of time required to configure the system and fire the separation pyros, and the amount of time the spacecraft takes to free-fall, turn to the proper attitude to start Powered Approach. The Backshell Separation sequence is shown in Figure 3.

Figure 3. Backshell Separation Sequence

The amount of time required to do the various stages in the backshell separation sequence is a combination of the system performance, desired behavior (allowing 0.2 s for the MLEs to warm up), and selection of parameters to ensure the backshell does not recontact the spacecraft as it fires up the MLEs and begins its Powered Descent. The entire sequence from initiating backshell separation until the spacecraft, now referred to as the Powered Descent Vehicle (PDV), starts to fall out of backshell is just over 1.4 s. Adding in the time required for the PDV to start Powered Descent, the controller must make a prediction of the altitude and velocity for the PDV just under 5s into the future. This is further discussed in the Backshell Separation Performance section later in this paper.

For MSL's EDL profile into Gale Crater, the vertical descent was expected to be approximately 85 m/s which would result in a Backshell separation occurs at approximately 1.6 km altitude.

POWERED DESCENT

The Powered Descent segment consists of four sub-segments:

1. Powered Approach
2. Constant Velocity Accordion
3. Constant Deceleration
4. Throttle Down

Powered Approach. During Powered Approach, the PDV follows a three-dimensional polynomial trajectory which was computed at BSS. As the PDV follows the polynomial, horizontal velocity is smoothly brought to zero while vertical velocity is simultaneously brought to 32 m/s. The target end point of the trajectory is 242 m above the surface and 300 m perpendicular to the plane of the entry trajectory. Since the PDV is actively slowing, the parachute and backshell will actually travel past the PDV and reach the surface ahead of the PDV. The 300 m divert distance is adequate to ensure the PDV does not land on the parachute or backshell. Once the endpoint of the Powered Approach trajectory is reached, the Constant Velocity Accordion begins.

Constant Velocity Accordion. When the on-board altitude estimate is computed at BSS, the spacecraft is still traveling horizontally and the TDS will almost certainly not be illuminating the exact point on the surface where landing will occur. This, as well as inherent system errors, could contribute to the altitude estimate to be different than the true altitude at BSS. To accommodate this, a period of constant vertical velocity is used to fly out this altitude error. This is termed the Constant Velocity Accordion.

Since the next sub-segment (Constant Deceleration) is set to begin at an altitude of 142 m, the target altitude for the beginning of the Constant Velocity sub-segment needs to be set to 242 m. This will allow for the case where the surface is 100 m closer than initially calculated. In this case, the length of the Constant Velocity Accordion is zero. In addition, enough fuel must be allocated for the Constant Velocity phase for the case where the surface is 100 m further away than initially calculated, in which case 200 m of altitude will need to be traversed.

The Constant Velocity sub-segment ends when the 142 m Constant Deceleration altitude is achieved.

Constant Deceleration. Beginning at an altitude of approximately 142 m above the surface, the PDV begins the constant deceleration segment. During this sub-segment, the PDV is decelerated from 32 m/s to 0.75 m/s. This is done at a constant deceleration rate roughly equivalent to 70% throttle setting.

The Constant Deceleration sub-segment ends at an altitude of 23 m above the surface at which point the Throttle Down sub-segment begins.

Throttle Down. At this point in the landing sequence, more than half of the initial 400 kg of fuel has been consumed. In order to maintain thrust equal to weight, the MLEs would need to be throttled back to thrust levels on the order of 20-25%. Since the MLEs operate less efficiently at these throttle settings, four of the MLEs are throttled back to their near-shutdown condition of 1%. This allows the four remaining MLEs to function in the more efficient range of 50% throttle.

The transition from eight to four MLEs introduces disturbances to the system. Therefore, a 2.5 s period of time is allotted for the disturbances to settle allowing for predictable and stable conditions for the next major segment of the landing: Sky Crane.

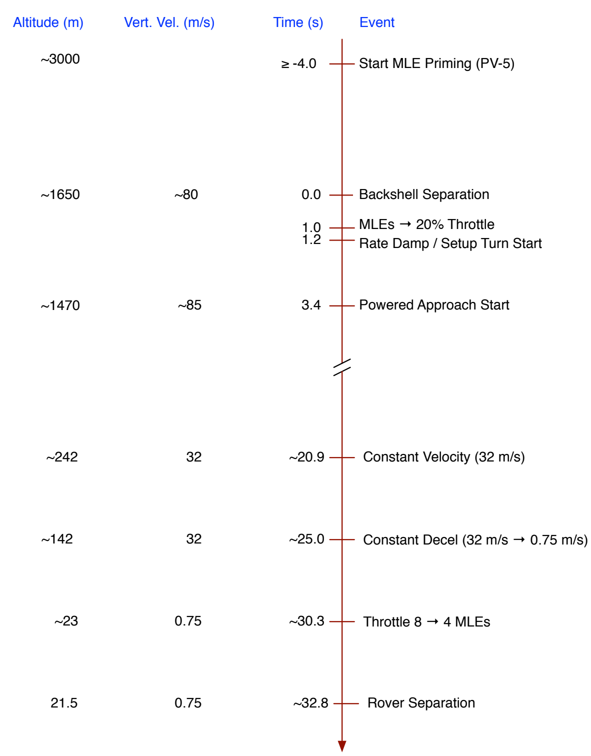

Figure 4. Powered Descent Timeline

SKY CRANE AND FLYAWAY

The touchdown technique employed by the MSL design is the most innovative portion of the EDL architecture. The technique, referred to as the Sky Crane maneuver, involves lowering the lander on a triple bridle from the slowly descending Descent Stage (DS) until the bridles are fully extended to a length of 7.5 m. A 0.75 m/s constant velocity vertical descent is maintained until rover touchdown is detected via persistence of bridle offloading as inferred from DS throttle commands. Figure 5 shows the Sky Crane configuration.

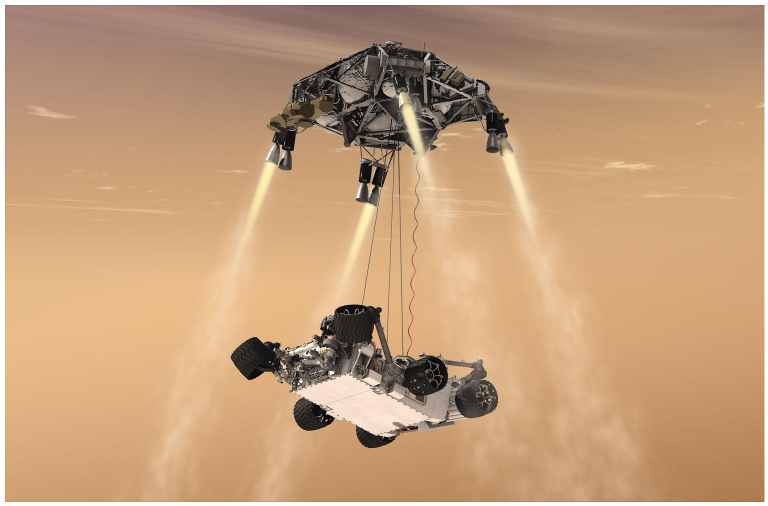

Figure 5. Sky Crane Configuration (Image Credit: NASA/JPL-Caltech)

Implementation of the Sky Crane architecture presents many advantages over historical touchdown methods, namely airbags and legged landers. The two body architecture keeps the engines and thrusters away from the surface, mitigating surface interactions like dust excavation and trenching, while enabling closed looped control throughout the touchdown event. The bridle decouples the touchdown event and associated disturbances from the DS controller. Additionally, rather than using a traditional touchdown sensor, touchdown is detected though a persistence of reduced throttle commands necessary to maintain the constant descent rate.

Due to the persistence of tethering during touchdown and low touchdown velocities, the system has greater touchdown stability and experiences lower impact loads than other landing systems. High stability and low loading, on par with rover driving loads, means that a separate touchdown system is not required and the egress phase can be eliminated. Rather, the rover's rocker-bogey suspension, which is specifically designed for surface interaction, is the touchdown system and it is properly positioned to begin operations immediately after touchdown.

Sky Crane Profile

The Throttle Down segment ends with the PDV descending at a rate of 0.75 m/s at an altitude of 21.5 m. At this point, separation pyros are fired to release the rover. Once the rover is released, the PDV is two separate vehicles: the DS and the Rover.

As the DS maintains a constant vertical velocity of 0.75 m/s, the rover is lowered on a triple bridle to 7.5 m below the DS through the use of an electromagnetic brake connected to a spool containing the three bridles. All of the bridles pass through a confluence point on the DS which is nearly collocated with the DS center of mass. In doing so, the Rover imparts minimal disturbance on the DS. Since all three bridles pass through a single point, it is impossible for differential loading of the bridle to produce moments on the DS. Figure 6 shows the BUD.

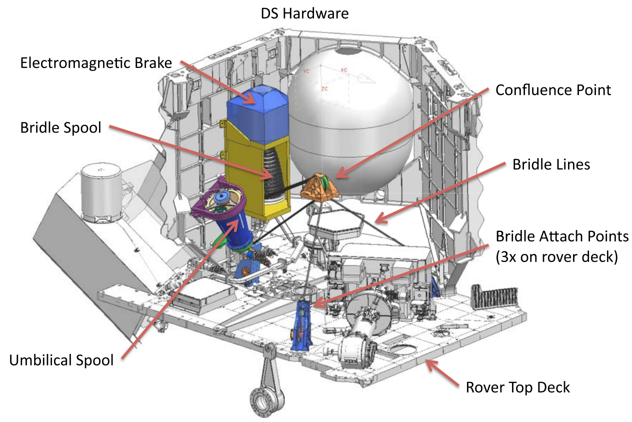

Figure 6. Bridle and Umbilical Device (BUD)

As the Rover is being lowered by the BUD, the wheels and suspension system are simultaneously being lowered from their compact stowed configuration to the “wheels down” configuration ready for landing. Figure 7 shows the sequence of the BUD deployment and mobility deployment.

Seven seconds after Rover separation from the DS, the bridle reaches its fully deployed length of 7.5 m at which point the bridle is at the end of travel and motion stops – this event is called “snatch”. Two seconds of post-snatch settling time is allotted to allow the DS to damp out any disturbances introduced by the snatch event. At this point, the system is ready for touchdown and the touchdown logic is enabled.

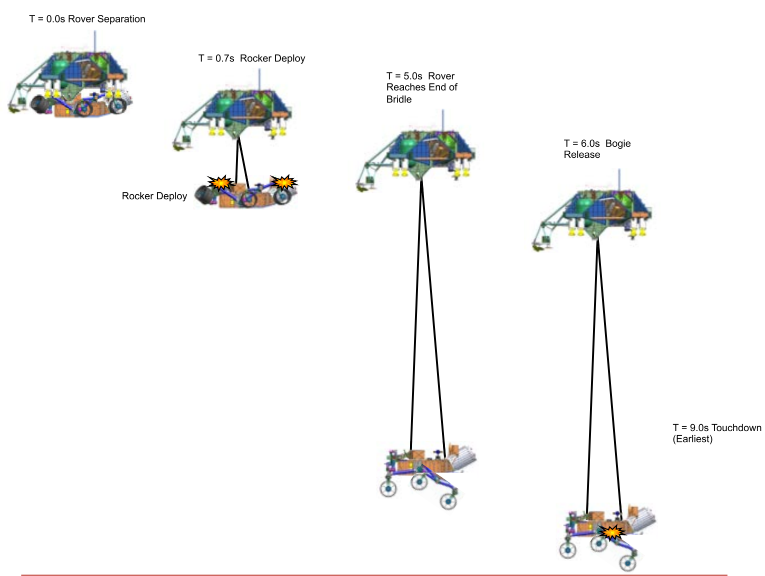

Figure 7. BUD and Mobility Deploy Sequence

Touchdown Logic

While the DS is following a constant velocity reference trajectory, the commanded vertical thrust is equal to the weight of the system. Prior to touchdown, the commanded vertical thrust will be equal to the gravitational acceleration times the combined mass of the DS and rover. After touchdown, the rover weight is supported by the surface, the bridle is offloaded, and the commanded vertical thrust is reduced to almost half of its previous value. This reduction in commanded thrust will persist after touchdown because the constant vertical descent reference trajectory ensures persistent offloading of the bride. The touchdown algorithm takes advantage of this inherent offloading by relying on the commanded vertical thrust to sense the touchdown event.

The touchdown logic is enabled 9 s after Sky Crane start (Rover Separation). Once enabled, a sliding 1.5 second window buffer of throttle commands is examined. At every point, the data is subjected to two tests to determine if touchdown has occurred. First, the data is examined to determine if there is a persistence of a constant state, i.e., the commanded throttle nearly constant over the window. If it is flat to within a settable tolerance, the average value is computed. If that average value is within an expected tolerance of the command necessary to support the DS mass only, touchdown is declared.

Flyaway

For the entirety of flight from launch pad at Kennedy Space Center until this point, control of the entire spacecraft including execution of the EDL sequence has resided in the computer located within the rover chassis. Once touchdown is declared, the DS halts vertical motion, control of the engines and IMU is transferred to the Flyaway Controller on the DS, and the bridles are cut by the rover. The BUD has built-in retraction springs to retract the now free bridles away from the Rover top deck.

Once the flyaway controller on the DS assumes control, it first holds the current altitude for 600 msec to allow sufficient time for the umbilical to be cut. After the requisite hold time, the MLEs throttle up and the DS ascends vertically for a predetermined amount of time. Then, the DS begins to execute a turn to approximately 50° pitch. The DS holds this attitude with the MLEs at 60% for 4 s. The hold, ascent, and turn take place within 2 s which corresponds to a total flyaway time of 6s. The DS will then ballistically fall to the surface at a distance of at least 150 m from the Rover.

Entry Descent and Landing is considered complete when the kinetic energy of all hardware is zero relative to the Martian surface.

POWERED DESCENT PERFORMANCE

This section will compare the in-flight performance with the pre-flight predictions from our end to end EDL simulation. Unless otherwise noted, all of the pre-flight predictions are based on an 8,000 run Monte Carlo simulation using the POST2 simulation[6] which was seeded with the final navigation solution prior to Entry.

The in-flight values given in this section are the values reported from on-board Navigation Filter. Comparison with the trajectory reconstructed by integrating the raw IMU measurements have shown the on-board velocity to be accurate to less than 0.1 m/s and altitudes to be accurate to less than 1 m.

Navigation Filter Convergence

As stated earlier, once the heatshield has been removed, the TDS is used to measure the spacecraft ground-relative altitude and velocity producing 20 measurements per second cycling through the 6 individual antennas. Once the Navigation Filter has ingested enough TDS data to produce a valid altitude and velocity solution, the Navigation filter is considered converged.

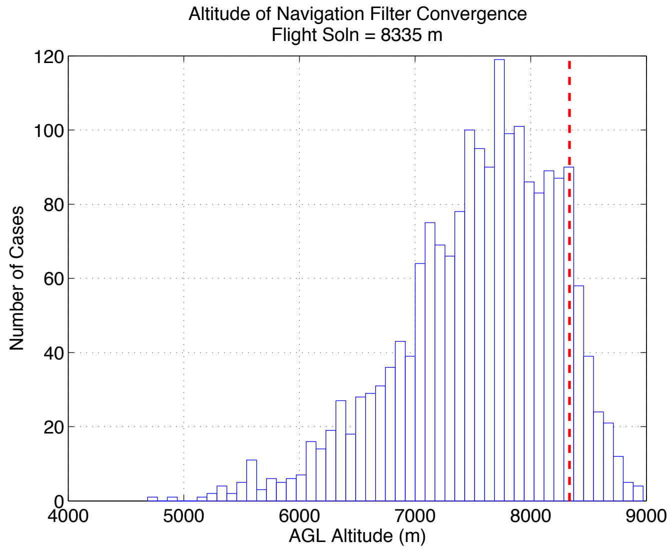

Figure 8. Altitude of Navigation Filter Convergence

Figure 8 shows the altitude at which the Navigation Filter converged in flight (red dashed line) compared to the pre-flight prediction (blue histogram). In this particular comparison, the pre-flight prediction is based on a 2000 run Monte Carlo which used a high-fidelity physics based radar model. This model was very computationally intensive and was only run periodically to confirm results from the more conservative and much faster statistical radar model. As seen in the Figure, the Navigation Filter converged at an altitude of just over 8.3 km, which is 1σ better than the mean. This is not surprising given assumptions needed to be made about the surface brightness in the radar spectrum where, naturally, conservative assumptions were made in the model.

Backshell Separation

Given the expected terminal velocity on the parachute of around 80 m/s, it was expected for the backshell separation to occur at an altitude of approximately 1.6 km. The exact altitude varies with velocity because the vertical velocity is used in real-time to predict where the spacecraft will be 5 s into the future, which is how long it takes from initiating BSS to the start of the Powered Approach phase.

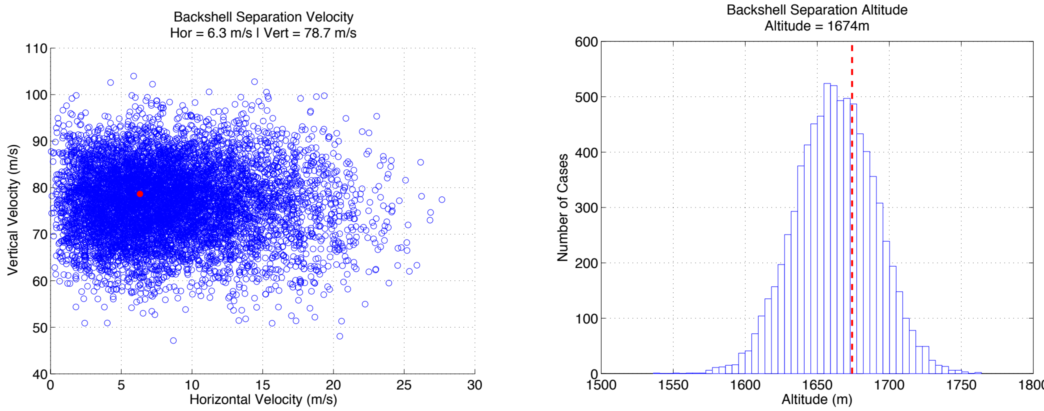

Figure 9. Backshell Separation Velocity (Left) and Altitude (Right)

Figure 9 shows the backshell separation velocity and altitude. The vertical descent rate of 78.7 m/s matched the pre-flight prediction well, as does the altitude of 1674 m.

Another important aspect to Backshell Separation is the angular rates on the spacecraft. The PDV extraction from backshell is aided guide rails to ensure that relative motion of the backshell with respect to the PDV does not cause any recontact to occur. However, high angular rates as the PDV is sliding down the guiderails could cause the guiderails to experience high loading and deform or even bind. The MSL systems was designed to be able to withstand rates as high as 50 deg/s in the transverse axes – that is, the axes that would contribute to wrist-mode of the spacecraft suspended from the parachute. A rate of 10 deg/s is allowed in the yaw axis.

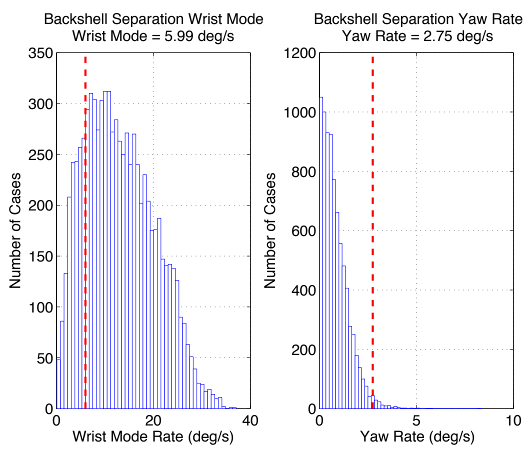

Figure 10. Backshell Separation Angular Rates

As seen in Figure 10, the angular rates of the spacecraft at BSS were extremely benign – The wrist mode was just under 6 deg/s with a yaw rate of 2.75 deg/s. This was somewhat expected given the low altitude of the Gale Crater landing site and corresponding long duration of descent under the parachute. The time from parachute deploy to BSS was 116.8 s, which allowed ample time for any wrist mode from parachute deploy to damp.

As stated in the Powered Flight Design section, the PD start logic predicts what the altitude of PDV *will* be at the time of Powered Descent start, almost 5s into the future. In order to ensure that Powered Descent would not start too low (and therefore not be able to stop in time), the design of the start logic assumed the spacecraft would be in free-fall from the time the BSS sequence was initiated until the Powered Approach segment began. In actuality, the spacecraft will be in near-constant velocity for about 1.4 s between deciding to perform BSS and actually separating from the backshell. In addition, the use of the thrusters for up to 2.2 s after BSS to null any residual angular rates and turn the PDV to the proper attitude to start Powered Approach results in a net thrust which serves to offset some acceleration due to gravity. As a result, the altitude at which powered approach actually starts will be higher than the ideal intended start altitude – i.e., the altitude loss during BSS will be less than the PD start logic predicts.

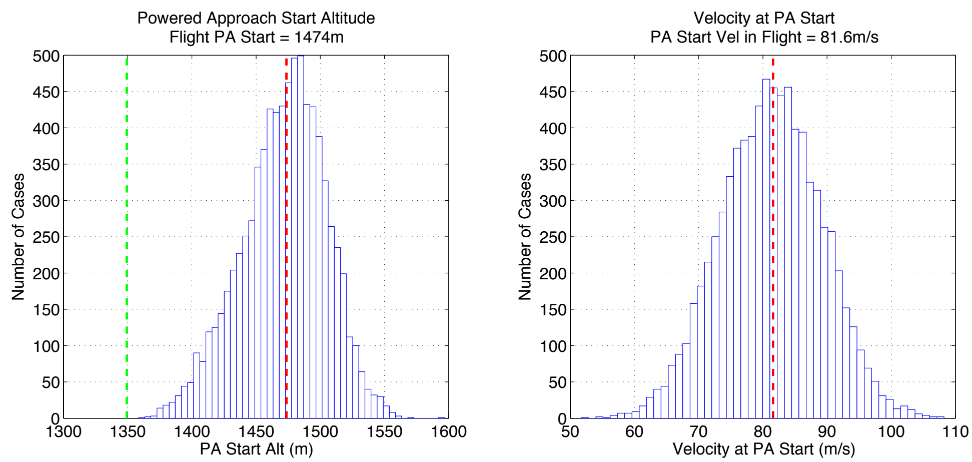

Figure 11. Powered Approach Start Altitude (Left) and Vertical Velocity (Right)

Figure 11 shows the in-flight altitude at the start of Powered Approach (red dashed line) compared to the pre-flight prediction (blue histogram). As indicated, the altitude of 1474 m at the start of Powered Approach was right on the mean of the pre-flight predictions. The green dashed line in the figure represents the PD start logic's prediction of the altitude at the start of the Powered Approach phase. Also as expected, the aforementioned free-fall assumption led to Powered Approach starting approximately 125 m higher than "ideal" – however this small conservatism does not lead to large inefficiencies and improving upon the PD start logic prediction was not pursued.

Finally, for reference the vertical velocity at Powered Approach start is shown in right-hand plot of Figure 11. Just as with the altitude, the velocity of 81.6 m/s is consistent with the mean of the pre-flight predictions.

Powered Approach

Recall that the two main purposes of the Powered Approach segment are to 1) execute a 300 m divert out of the current plane of travel in order to avoid landing on or near the backshell on the surface, and 2) bring the PDV to a vertical-only descent at 32 m/s at an altitude of 242 m above the surface.

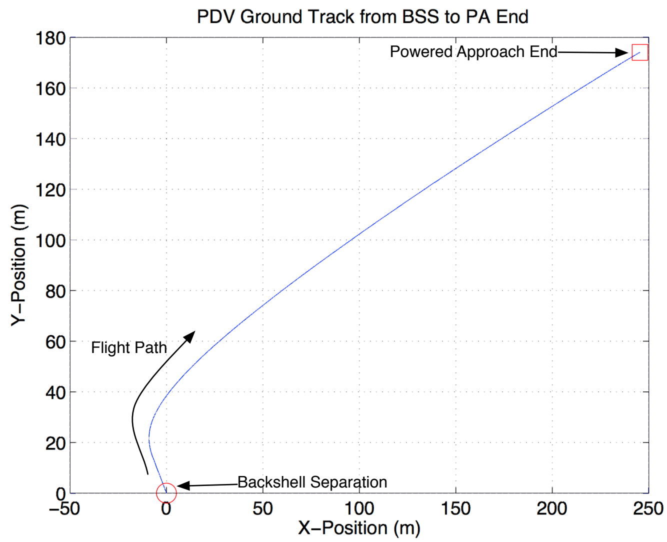

Figure 12. Ground Track from Backshell Separation (circle) to Powered Approach End (square)

The ground track of the PDV during powered approach is shown in Figure 12. Backshell separation occurs at the circle in the figure. Shortly after BSS, the powered approach segment begins and the 300 m divert is clearly visible. It should also be noted that divert is perpendicular to the initial path at BSS.

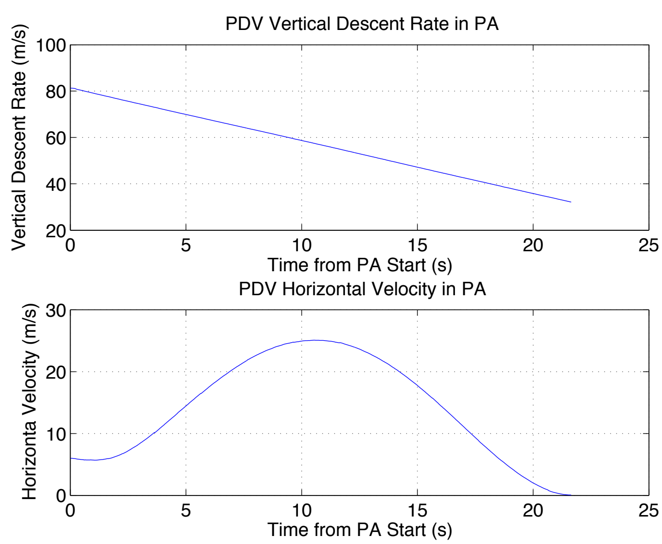

Figure 13. Velocity During Powered Approach

Figure 13 shows the velocity profile of the PDV during the Powered Approach phase. In the top plot, the desired linear decrease in velocity from just over 80 m/s to 32 m/s is seen. The bottom plot shows the horizontal velocity. As the PDV performed the divert, the horizontal velocity was increased to move laterally and then decreased to zero horizontal velocity by the end of Powered Approach.

As the PDV performed the divert maneuver, it was necessary for the spacecraft to “tilt” in order to direct a component of the thrust horizontally. However, since the TDS antennas are fixed to the PDV, they are also tilted with it. If enough antennas lost line of sight with the surface, the Navigation filter would no longer be able to make a TDS-informed velocity estimate and would need to propagate the velocity on the IMU. Since this condition would only exist for a second or two, it was not considered a problem. Once the TDS beams were again in line of sight with the surface, the Navigation Filter would once again pick up using the TDS-informed velocity estimates.

It was noted in simulation that when the TDS measurements would come back from this temporary loss of sight with the surface, that there would be a step-correction in the velocity estimate of the spacecraft because the IMU propagated velocity would diverge slightly from the velocity once the measurements returned. These corrections were, in general, small – on the order of 0.2 m/s or less. While the system could handle these discontinuities in the velocity estimate, it was decided that it would be good practice to not have the TDS lose sight of the surface at all during the divert under nominal conditions.

The Navigation Filter would ignore measurements from the TDS if the antenna boresight was off vertical by more than 60 deg. The antennas used during powered approach consisted of one antenna pointed directly “down” along the spacecraft z-axis direction and three antennas each tilted 20 deg from the “down” direction. With this configuration, it would allow a maximum tilt of 40 deg before one of these 4 antennas would be ignored by the Navigation Filter. Therefore, it was decided to have a design goal of 35 deg maximum off vertical angle during Powered Approach.

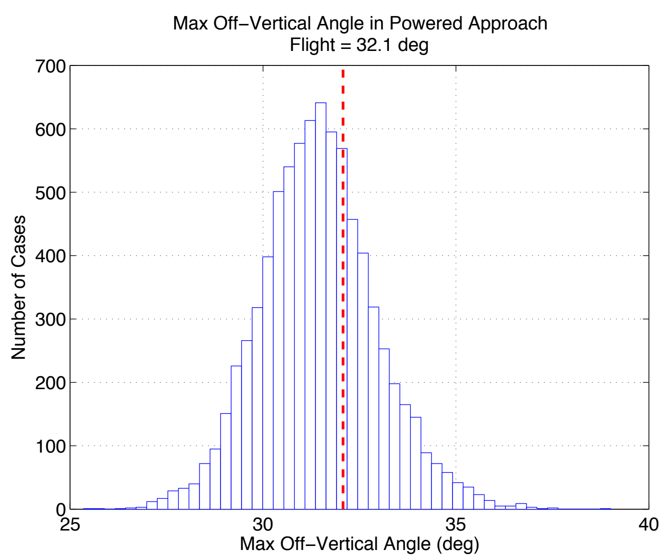

Figure 14. Maximum Off-Vertical Angle of the PDV during Powered Approach

Figure 14 shows the pre-flight maximum off-vertical angle prediction of the PDV during powered approach (blue histogram) and the in-flight value (red dashed line). As seen in the figure, the off-vertical angle was less than 1 deg away from the mean predicted value. Also of note is no TDS measurements were ignored in-flight due to the off vertical angle criteria and valid velocity measurements were made throughout all of powered flight.

Constant Velocity Accordion

During the Powered Approach phase, the TDS is used to make velocity and altitude measurements, however the altitude is ignored. This design choice was made so the system would not spend fuel chasing an altitude measurement made when it was known that the TDS antennas would not be looking at the surface near where the eventual landing site would be. This is due to the tilt necessary to perform the divert discussed in the previous sub-section.

At the end of the Powered Approach phase the PDV is now traveling vertically at an nominal altitude of approximately 240 m and the TDS is illuminating the spot on the surface directly beneath the spacecraft and therefore the eventual landing site. It is at this point the spacecraft can make a much more accurate altitude measurement and be in a better position to fly out any altitude error which existed in the altitude estimate at backshell separation. This error is flown out during the Constant Velocity (CV) accordion.

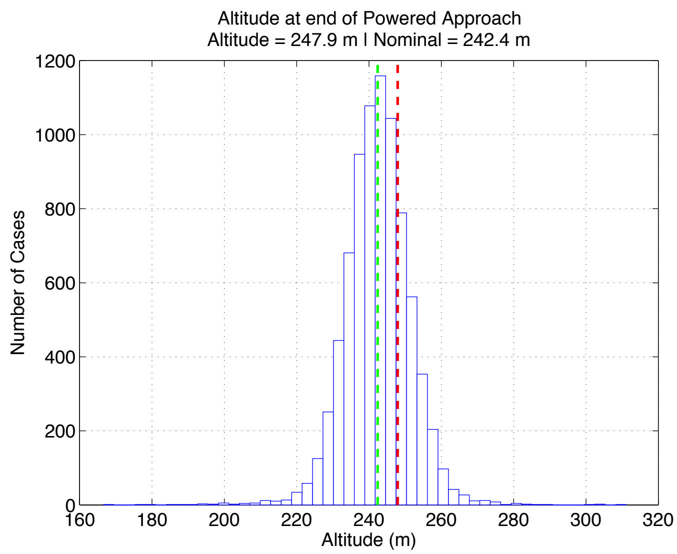

Figure 15. Constant Velocity Start Altitude

Figure 15 shows the starting altitude of the CV phase. The pre-flight prediction histogram is shown in blue and the in-flight altitude is shown with the red dashed line. As seen in the figure, the nominal altitude at the start of CV is 242.4 m. In flight, the PDV was at an altitude of 247.9 m, which indicates that at backshell separation, the on-board altitude estimate produced by the Navigation Filter was off by less than 6m. The post-landing position indeed is consistent in showing that the eventual touchdown area was in a relatively flat area of the landing site.

Figure 16 shows the pre-flight performance predictions of the altitude at the end of the CV phase compared to the altitude seen in flight. As seen in the figure, in-flight performance was nearly perfectly on the mean.

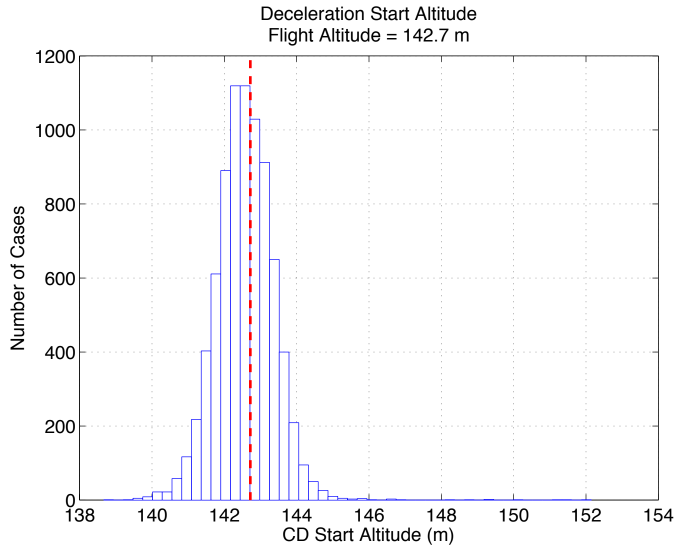

Figure 16. Constant Deceleration Start Altitude

Constant Deceleration

At the end of the CV phase the PDV is descending at a rate of 32 m/s and is 142 m away from the surface. The design of this phase was to have the PDV generate a sensed vertical acceleration of 8.0 m/s^2 – however, the system is closed loop and is allowed to vary this acceleration command (within limits) as needed to ensure it reaches the desired end condition of 23.1 m altitude at 0.75 m/s.

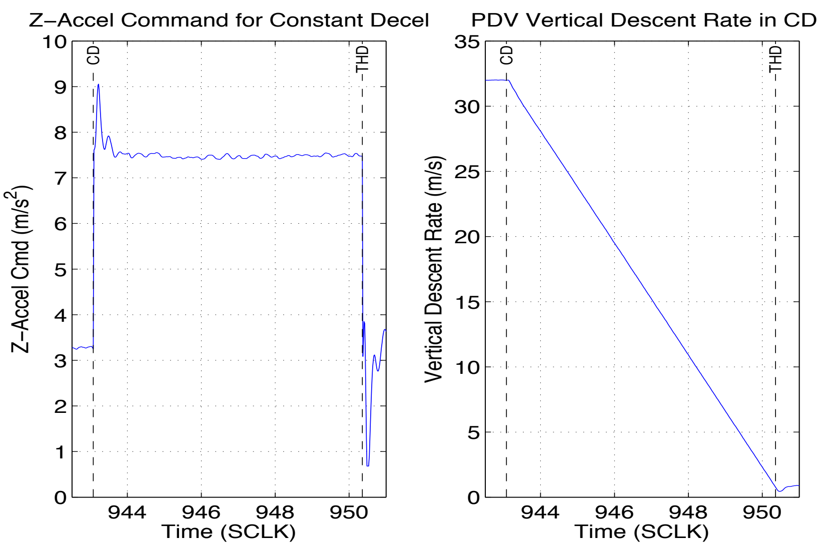

Figure 17. Acceleration Command (left) and Descent Rate (right) during Constant Deceleration Phase

Figure 17 shows the in-flight acceleration command and the vertical descent rate during the CD phase. As shown in the left-hand plot, the acceleration command was about 7.5 m/s^2, which was under the design of 8.0 m/s^2. Post-landing analysis of the MLE performance shows that the engines performed better in flight than what was included in the pre-flight simulations (this aspect is still under investigation) As a result, the system needed to command less acceleration to achieve the desired 8 m/s^2 command.

The right-hand plot of Figure 17 shows the velocity of the PDV during the CD phase. The desired velocity of 0.75 m/s can be seen at the end of the CD phase. Figure 18 shows the in-flight altitude of the PDV vs the pre-flight prediction. The in-flight performance is less than 0.4m away from the ideal altitude. It should be noted the design goal was less than 1m of error.

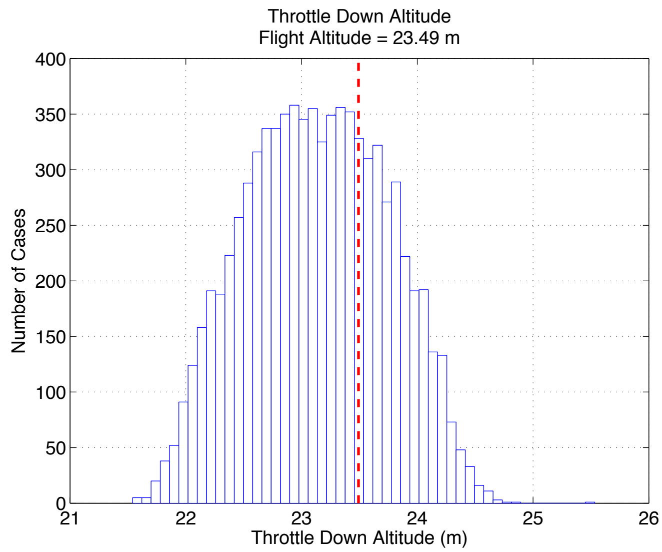

Figure 18. Altitude at the end of the Constant Deceleration Phase (Throttle Down)

Throttle Down

A side effect of shutting down half of the engines which have been flying the PDV to this point is that the remaining four must throttle up to compensate. This sudden impulse causes a disturbance to the attitude and velocity of the PDV. Built into the timeline is 2.5 seconds to allow this disturbance to settle.

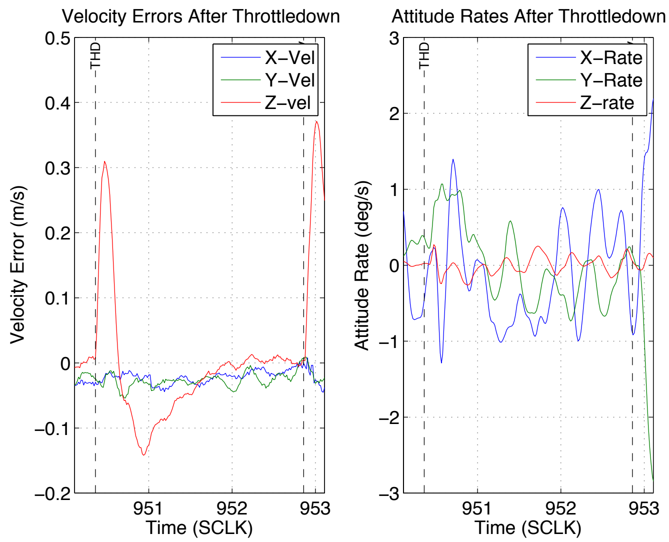

Figure 19. Velocity and Attitude Rates at Throttle Down

Figure 19 shows the velocity and attitude rates of the PDV at throttle down and the 2.5s settling time. In the left-hand plot, the throttle down disturbance to the PDV is visible in the Z velocity, but has recovered about 1.25 s after throttle down. In the right-hand plot, there is very little attitude rate disturbance seen. It should be noted that it was a requirement on the system that this rate be less than 3 deg/s at the end of the settling period. As seen in the plot, the system was not near this limit.

Sky Crane

At the end of the Throttle Down and Settling period, the system is ready to perform the Sky Crane maneuver. In order to ensure a clean separation of the rover, it is desired to have the system be a quiescent as possible at the moment of separation. In order to accomplish this, a requirement of keeping the PDV within 3 deg of vertical with attitude rates of less than 3 deg/s about the transverse axes (which would contribute to off vertical angle) and a yaw rate of less than 1 deg/s.

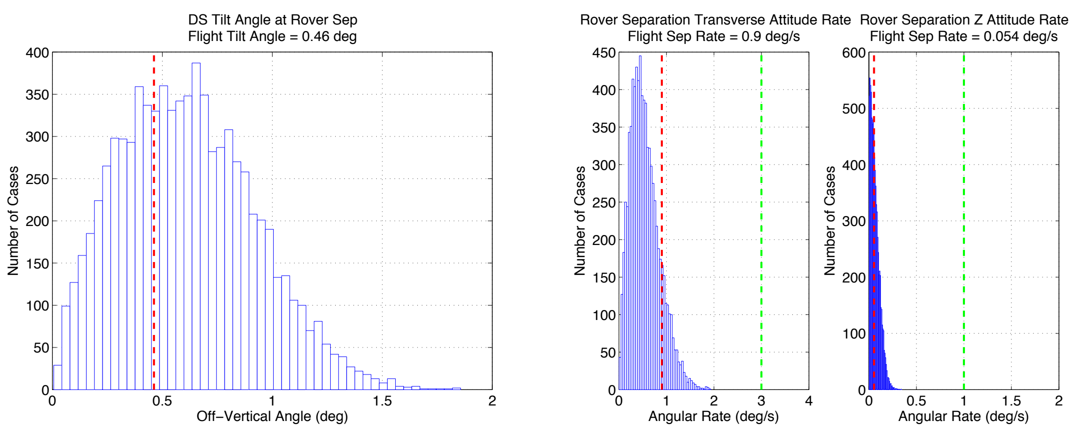

Figure 20. Rover Separation Attitude and Attitude Rate Conditions

Figure 20 shows the attitude and attitude rate at Rover Separation. The figure contains the pre-flight predictions in the blue bars, the requirements with the green dashed lines, and the in-flight values with the red dashed line. As seen in the figure, the system meet all of the rover separation requirements with significant margin.

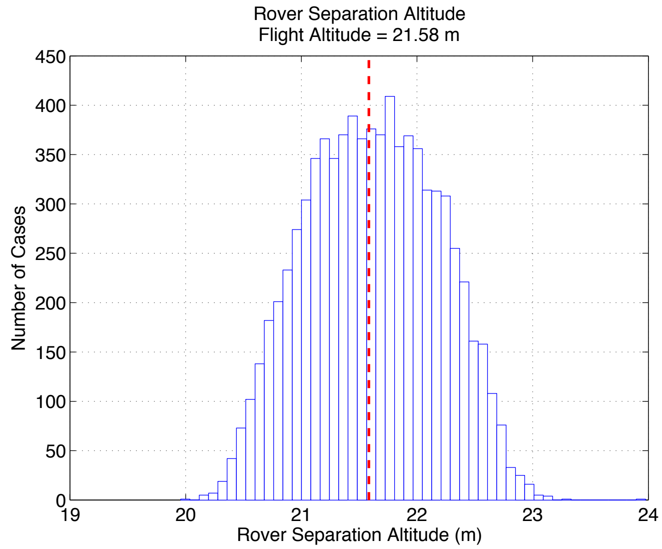

Figure 21. Rover Separation Altitude

Figure 21 shows the rover separation altitude. At Rover separation, the ideal expected altitude was 21.3 m. The altitude at rover separation in flight was within 0.3 m of this desired altitude – well within the 1m design goal.

When picking the altitude at which rover separation would occur, an allowance for up to 5 m of altitude error was built in. This would allow the on-board altitude estimate at the time of Rover Separation to be off by up to 5 m and still allow enough time for the rover to fully deploy and settle before touching the surface. Note that this 5 m is greater than our design goal of 1m – this was done to accommodate slopes and rocks as well as to add margin to the system. As was shown in Figure 21, the estimate error at this point was much less than the allocated value.

Since the system should be descending at a constant rate, and the altitude error at rover separation was extremely small, it would be expected that the system should take 15.67 s from the time of rover separation until the rover touches down on the surface. However, examination of the flight data shows a 17.9 s from rover separation to first contact. Investigation of this error is covered in Sericchio, et al. and is due to a small error in the on-board gravity model in the Navigation Filter. This error, coupled with no longer using the TDS to measure vertical velocity after rover separation led to a velocity estimation error.

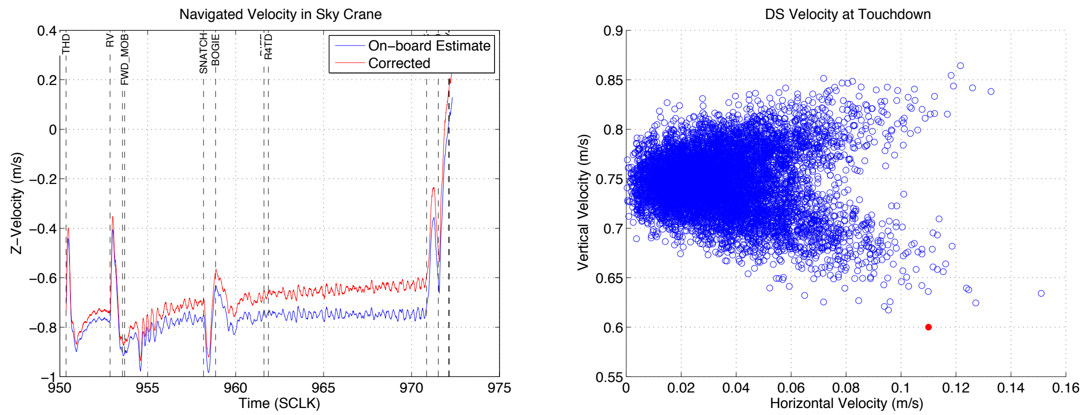

Figure 22. Velocity in Sky Crane

Figure 22 shows both the on-board velocity estimate and corrected velocity estimate during Sky Crane. Also in the figure is the pre-flight predictions of the horizontal and vertical velocity at touchdown (right-hand plot, blue circles) and the in-flight touchdown velocity (red dot). As seen in the figure, the on-board estimate shows the proper descent rate, however the corrected estimate shows that the descent rate was getting slower as it descended. This divergence is what lead to the extended time between rover separation and touchdown. However, since the error was in a direction that led to a slower than expected touchdown, there was no post-landing concern of damage to the rover.

Flyaway

Initially, it was determined that 150 m was the minimum safe distance to avoid debris from a rupturing pressure tank upon Descent Stage impact. To achieve this distance goal, 22 kg of fuel was allocated for Flyaway. However, later development of the flyaway controller showed that a mean distance of 520m was possible with this same amount of fuel. It was decided to keep this allocation and achieve a greater flyaway distance.

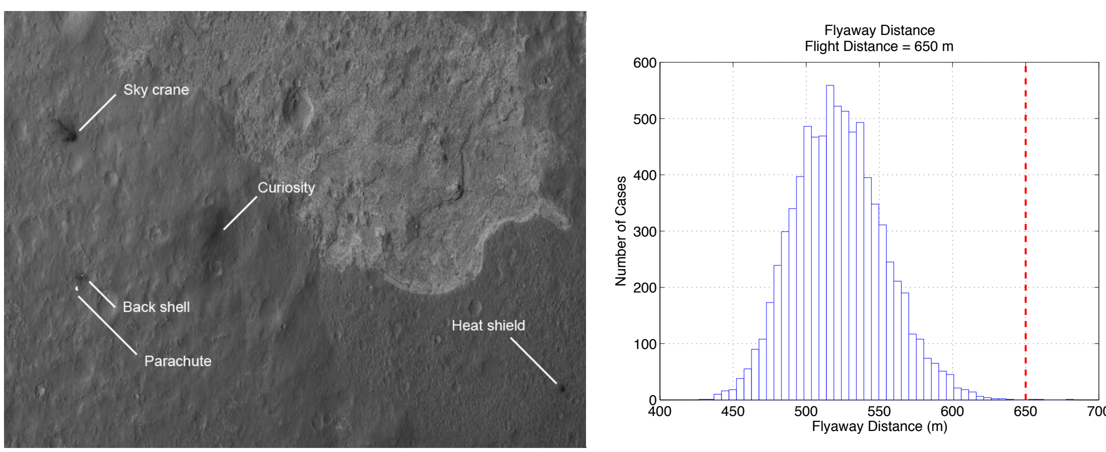

Figure 23. Landing Site (Image Credit: NASA/JPL-Caltech/Univ. of Arizona) and Flyaway Distance

Figure 23 shows a HiRise image (left) of the MSL landing site showing the impact of the descent stage relative to the Rover. The right plot shows the pre-flight flyaway distance prediction with the red dashed line indicating the in-flight performance. As seen in the plot, the in-flight fly-away performance of 650 m exceeded that of the pre-flight predictions. This is likely attributed to the better than simulated performance of the MLEs in-flight as discussed previously.

CONCLUSION

The Powered Flight portion of the Mars Science Laboratory Entry Descent and Landing system is the most complex and daring to date in the Mars exploration program. Through years of development, testing, and planning, its in-flight performance held few surprises and was refreshingly uneventful in that the system behaved almost exactly as the pre-flight predictions foretold. Further investigation of the Sky Crane system is still work to go with a more detailed IMU-based integration of the flight path and velocities. However, all indications – as outlined in this summary paper, are the MSL EDL Powered Flight segment performed as-expected and as-designed and is a testament to a well thought out design and brilliantly executed plan.

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