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Odyssey Preparations for and Role in Curiosity Entry Descent and Landing With Focus on Attitude Selection

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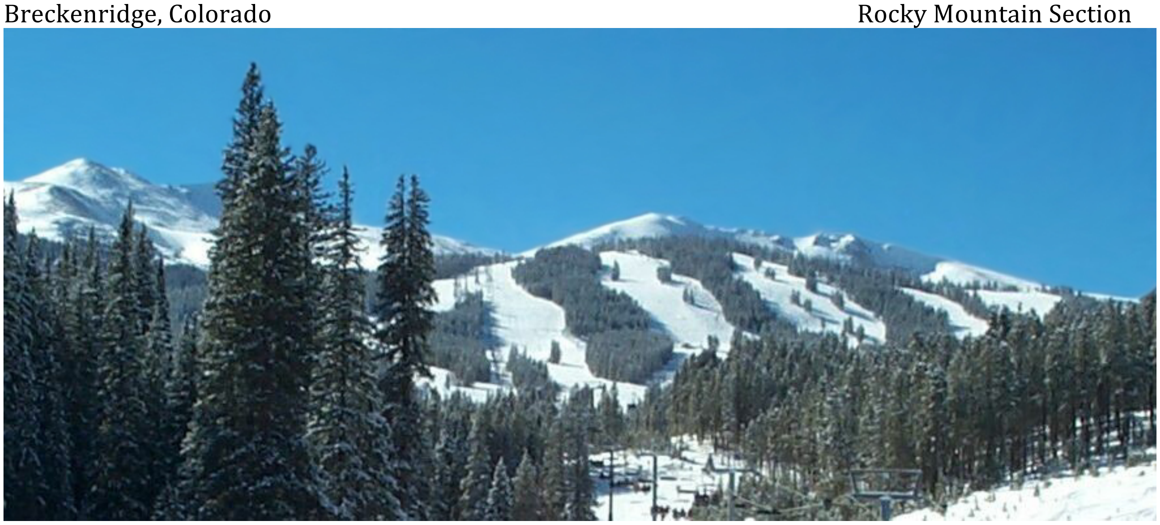

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Odyssey Preparations for and Role in Curiosity Entry Descent and Landing With Focus on Attitude Selection

Noel H. Hughes, John Balke*

The Odyssey Mars Orbiter provided real time bent pipe data relay of data from the Mars Science Laboratory, Curiosity, during the Entry, Descent and Landing (EDL) phase of the mission. In this paper we will describe the motivation for having real time and non-real time relay communication from Curiosity during EDL and the requirements and objectives applicable to Odyssey to effect such communication. Next we describe the Odyssey vehicle and mission and outline the events and actions by the Odyssey team leading up to Curiosity EDL, including the loss of a reaction wheel which led to two safe mode entries and subsequent recovery efforts. In the remainder of the presentation we will describe how requirements, imposed both by Curiosity EDL and by Odyssey health and safety and communication restrictions, drove the attitude profile of Odyssey during EDL and the process by which this attitude profile was developed.

INTRODUCTION

The 2001 Mars Odyssey vehicle has been in orbit around Mars for over a decade and recently became the longest lived vehicle orbiting Mars. Odyssey's mission is two fold, 1) gather scientific data with on-board sensors and 2) provide communication relay for vehicles on the Martian surface. Odyssey has transmitted over 85% of the data returned from the rovers, "Spirit" and "Opportunity" and was the primary relay for the "Phoenix" lander. In this role as a communication relay platform, Odyssey was tasked to provide communication relay for the Mars Science Laboratory (MSL) mission, "Curiosity". Relay operations, most commonly, are performed by receiving data from a surface vehicle and storing it for later transmission to Earth. However, Odyssey was also directed to provide real time, "bent pipe", communication during the Entry Descent and Landing (EDL) phase of the mission. To accomplish this, the Odyssey Spacecraft Team (SCT) planned and successfully executed operations to modify the existing orbit and to fly at an off nominal attitude that provided simultaneous reception from the Curiosity vehicle and high rate transmission to Earth. The SCT also overcame several unexpected events, including a reaction wheel anomaly and two resulting safe mode entries, all within two months of Curiosity EDL.

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MARS SCIENCE LABORATORY, CURIOSITY

As the newest and most ambitious Mars mission to date, MSL received a great deal of attention from both the scientific community and the general public. It was launched November 26th, 2011 and performed Entry, Descent and Landing on August 6, 2012, surviving the "seven minutes of terror". Once the MSL landing stage separated from the cruise stage, direct to Earth communication was limited to very low bandwidth channels, capable of providing only rudimentary data. Due to expected atmospheric ionization and the landing site geometry, shown in Figure 1, all direct to Earth communication with the MSL lander became unavailable during EDL several minutes before touchdown.

The Odyssey Spacecraft Control Team (SCT) was directed to provide real time (except for the 14 minute light time delay inherent in communications with Earth) or "bent pipe" communication with MSL during EDL operations. The requirements levied by the MSL team were for Odyssey to be at a given latitude and longitude at a specified time to be within the beam pattern of the MSL low gain antenna and to maintain attitude such that MSL remain within 30 degrees of the Odyssey UHF antenna boresight from atmospheric entry interface to one minute after landing.

Target Landing Site: Gale Crater

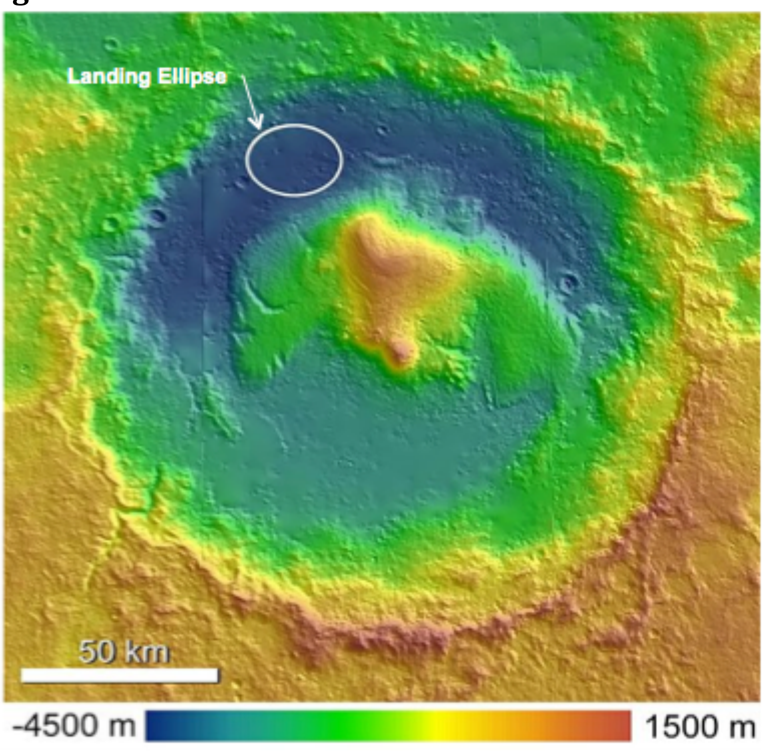

Figure 1 Gale Crater Topography

As can be seen from Figure 1, the MSL targeted landing ellipse lies on the floor of Gale crater about 4500 meters below the mean Mars surface. Mt. Sharp, named after Robert P. Sharp, an American geologist and expert on Mars surface geology who died in 2004, rises to an altitude of 1500 m above the mean Mars surface for a total height from the floor of Gale crater of 6000 m.

Entry, Descent and Landing (EDL)

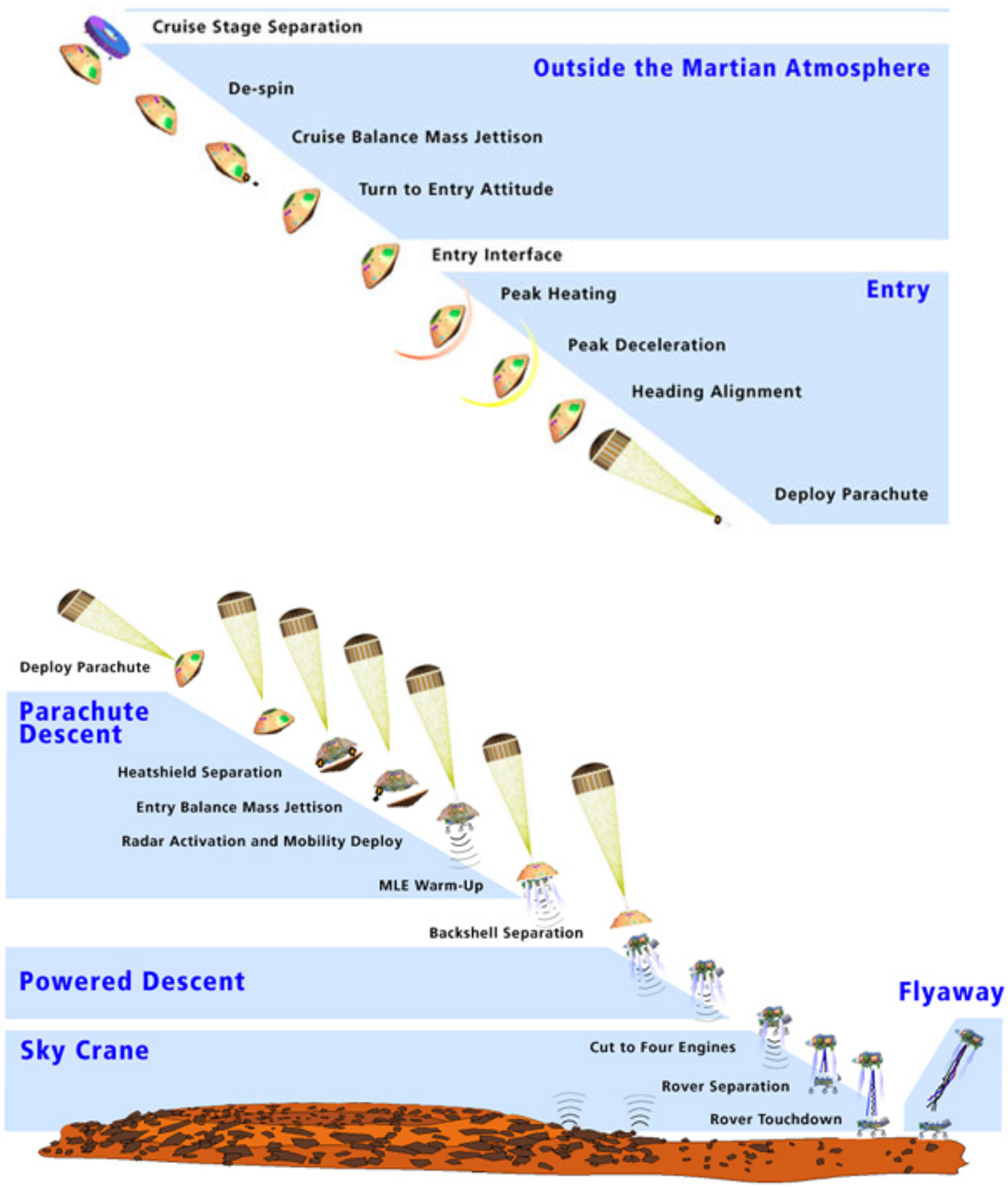

Figure 2 MSL Entry, Descent and Landing Sequence

Figure 2 shows the sequence of events during Curiosity EDL. Odyssey provided real time bent pipe communication to Earth starting after the point of peak deceleration and before parachute deployment.

ODYSSEY

Mission History

Lockheed Martin Company (LMCo) built and operates the Odyssey Mars Orbiter under contract to NASA, Jet Propulsion Laboratory (JPL). Odyssey was launched aboard a Delta launch vehicle, April 7, 2001; it accomplished Mars Orbit insertion October 24 of the same year. Odyssey circularized its orbit using aerobraking, thus saving roughly 200 kg of propellant, and achieved its operational, or "mapping", orbit in January 2002.

Since becoming operational Odyssey has returned a wealth of scientific data including information on the Mars radiation environment, surface composition and detailed surface imaging in both optical and multi band infrared spectra. In 2002 Odyssey detected large masses of subsurface water ices. Odyssey also has served as a communications relay for the Phoenix lander and the Mars Exploration Rovers, Spirit and Opportunity. In December of 2010 Odyssey became the longest lived spacecraft at Mars.

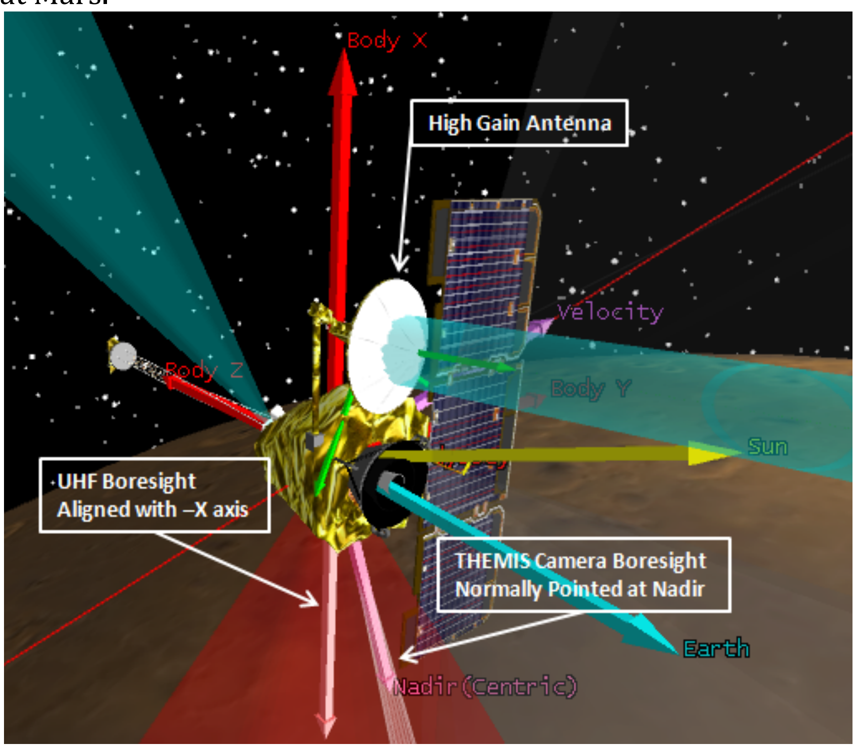

Figure 3 Odyssey Spacecraft in Mars Orbit

Vehicle Description and Current Operations

Figure 3 shows the general configuration of the Odyssey Mars Orbiter in its nominal flight attitude. Odyssey's current primary scientific instrument is the Thermal Emission Imaging System (THEMIS). In the design of the vehicle, THEMIS was mounted with its boresight 17^o forward of the vehicle –X axis, close to the center of the range of vehicle principal inertial axis as gimbaled appendages are moved; flying with THEMIS pointed at nadir minimizes gravity gradient torque on the vehicle. The boom shown in Figure 3 mounts the Gamma Ray Spectrometer; the boom is aligned with the vehicle Z axis. In nominal operation, Odyssey flies with THEMIS pointed at nadir and the Z axis aligned with the orbital momentum vector. The High Gain Antenna (HGA) is the primary means of communication with Earth. The HGA is mounted on a two axis gimbal whose travel envelope is roughly aligned with the vehicle –Z axis. The UHF antenna is used for communication with vehicles, which are usually on the surface of Mars; its boresight is aligned with the vehicle –X axis. As with earlier surface missions, this antenna is used for data reception from MSL during and subsequent to EDL.

Odyssey primary attitude control actuators are three Reaction Wheel Assemblies, or RWA's; there are four on board, three primary, aligned with the three vehicle coordinate frame axes, and a nominally inactive fourth, oriented between the mounting directions of the other three which could be used in case of failure of any of the other three. This backup RWA is called the "skew" wheel.

Attitude determination sensors consist of a star camera for external reference and three axis Ring Laser Gyros (RLG's).

PRE-EDL ODYSSEY EVENTS, SPACECRAFT TEAM ACTIVITIES

Early Operations Development

Odyssey team activities to support MSL EDL began in September of 2011. Activities fell generally under two categories, orbit modification, planned by the JPL Navigation team, and attitude profiles, planned by the LMCo GNC team. Orbit modification was required to place Odyssey at a time and location coordinated with Curiosity EDL. Attitude profile development included selection of the attitude to be flown during the MSL entry to landing period, management of momentum, i.e. RWA speeds, during the slews to and from the EDL attitude and at the EDL attitude and providing for power collection and thermal safety during all operations.

Odyssey Orbit Modification via Momentum Management

Odyssey flies a Sun synchronous orbit of period approximately 118 minutes. Fortunately, the local mean solar time Odyssey was flying leading up to EDL, approximately 15:56 at the descending node, was very close to that required to support the event; thus, no orbit plane change was required. However, the phasing or true anomaly at the time of EDL was late by approximately 35 minutes or more than a quarter of an orbit. The JPL navigation team determined that the phasing could be modified to support EDL operations by utilizing the effects of thrusting that occurs during RWA momentum dumping or desat operations.

Because of Odyssey Reaction Control System (RCS) thruster location, thrusting to effect momentum dumping produces a net linear impulse or delta velocity. Nominally, Odyssey attitude is controlled so as to fly a constant offset from the rotating velocity vector, local horizontal coordinate frame. During the period leading up to EDL, Odyssey flew with the vehicle Z axis, which is roughly the minimum moment of inertia principal axis, normal to the orbit plane to minimize gravity gradient torque and resultant momentum accumulation. Flying this attitude, vehicle X and Y axis momentum couple more or less completely through an orbit while Z axis momentum couples very little or not at all with the other two axes.

Again, because of thruster location, thrusting to produce X axis torque is only about 25% as effective as for Y or Z axis. To maximize efficiency, desats are timed to occur as X axis momentum is passing through zero and Y axis momentum is at a maximum in absolute value. This configuration occurs twice per orbit, once as Y axis momentum is at a maximum and once at a minimum. A desat with positive Y momentum produces a linear impulse component parallel to the velocity vector; dumping negative Y momentum produces impulse anti-parallel to the velocity vector. By controlling which of the two X axis momentum zero crossing points is used for executing desats, the orbit radius or semi-major axis can be controlled and thus the phasing.

Studies by the Odyssey navigation team following the decision in late July 2011 to land Curiosity at Gale Crater indicated that there was enough authority using desat management to change Odyssey phasing to meet EDL requirements. Management of desats to meet EDL requirements was initiated in September, 2011.

Odyssey EDL Inertial Hold Attitude Selection

Selection of attitude for Odyssey to support MSL EDL began conceptually in October of 2011; detailed attitude development began in early December, after MSL launch November 26, with the availability of a preliminary MSL trajectory in early December. With EDL inexorably scheduled for August 6, 2012, there was little time for major software tool development. The challenge became to develop, test and

verify attitude profiles using existing tools with little, if any, additional software development. Somewhat similar operations had been conducted in 2008 to support EDL of the Phoenix lander.

The primary tools used for attitude profile development development were 1) an existing simulation of the Odyssey vehicle, called attprof, 2) various pre-existing and developed Matlab® scripts and 3) Satellite Tool Kit®. Quaternions were used as the preferred attitude description notation. The J2000, Mars Centered Inertial (MCI), or Mars IAU, coordinate system was used throughout.

One objective of Odyssey attitude was to minimize the size of the attitude changes, or slews, from nominal operational attitude. To effect this, the starting attitude was taken as the nominal nadir following attitude at the time of MSL landing, $\boldsymbol{Q_0^{Ody}}$, relative to the MCI This was derived by running the simulation, attprof, in normal Odyssey operational mode through the time of MSL landing. The MSL trajectory was delivered by the Jet Propulsion Laboratory Flight Operations Group in the form of ephemeris kernels (SPK) files. The Odyssey to MSL vector, $\boldsymbol{V_{O-M}^{MCI}}$, was extracted from the MSL SPK using functions from the NASA Matlab Spice, mice, library, and normalized. $\boldsymbol{V_{O-M}^{MCI}}$ was transformed into the Odyssey body coordinate frame via Eq. (1).

$$\boldsymbol{V_{O-M}^{Ob}} = \boldsymbol{Q_0^{*Ody}} \otimes \boldsymbol{V_{O-M}^{MCI}} \otimes \boldsymbol{Q_0^{Ody}} \quad (1)$$

where $\otimes$ denotes quaternion multiplication and * is denotes the conjugate.

The delta quaternion that rotated Odyssey from nominal nadir attitude to an attitude pointing the boresight of the UHF antenna at MSL at landing was derived using Eqs. (2) through (4).

Rotation axis vector:

$$\boldsymbol{V_{rot}} = [-1\ \ 0\ \ 0]\ \boldsymbol{X}\ \boldsymbol{V_{O-M}^{Ob}} \quad (2)$$

where $\boldsymbol{X}$ is the cross product operator.
The rotation angle was derived:

$$\boldsymbol{\theta_{rot}} = [\boldsymbol{-1\ 0\ 0}]\ \bullet\ \boldsymbol{V_{O-M}^{Ob}} \quad (3)$$

$$\boldsymbol{Q_1^{\nabla}} = [\ \boldsymbol{V_{rot}}\ \boldsymbol{sin}\left(\frac{\boldsymbol{\theta_{rot}}}{\boldsymbol{2}}\right)\ \ \boldsymbol{cos}\left(\frac{\boldsymbol{\theta_{rot}}}{\boldsymbol{2}}\right)] \quad (4)$$

The attitude which pointed the Odyssey UHF antenna at MSL at landing was derived via Eq. (5).

$$Q_1 = Q_0^{Ody} \otimes Q_1^{\nabla} \quad (5)$$

Analysis showed that it was impossible to point the HGA at Earth while flying this attitude. The first attempt to find an attitude that supported HGA to Earth pointing consisted of rotating the vehicle starting at $\boldsymbol{Q_1}$ by +/-45 degrees about the X spacecraft axis (rotation about the X axis does not affect pointing of the UHF antenna) using attprof, which attempts to point the HGA at Earth but will not violate the gimbal space boundaries. From this, the trajectory of the Earth vector relative to Odyssey during the rotation was determined. Figure 4 depicts the HGA gimbal space both in Cartesian inner and outer gimbal angles and displayed in a view looking out the –Z spacecraft body axis; the HGA pointing vector trajectory during the rotation is superimposed on the gimbal space. As can be seen from the figure, the simulation could not point the HGA at Earth at any point in the rotation since the HGA was against a boundary of the gimbal space. The minimum angle between the HGA boresight and the Earth vector was slightly more than five degrees.

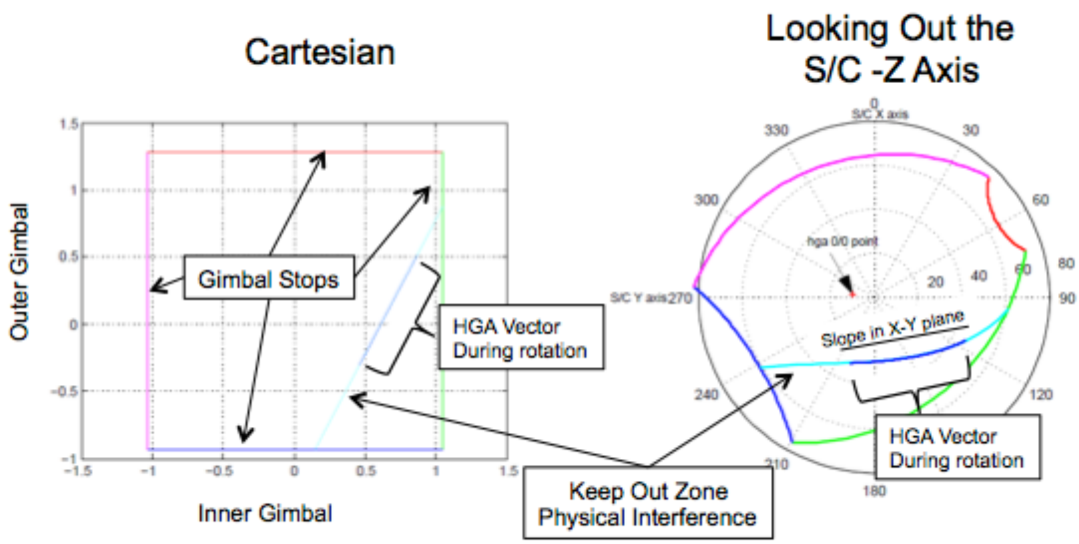

Figure 4 HGA Gimbal Space

The next attempt to find an attitude providing HGA Earth pointing was to derive a rotation, represented by a quaternion, which would bring the Earth vector within the gimbal space. The rotation axis for the quaternion was derived from the slope in the X-Y plane of the HGA trajectory, as shown in Figure 4, setting the Z component of the rotation axis to zero; the rotation angle used was six degrees. Starting at the attitude where the minimum HGA to Earth vector occurred, this rotation quaternion was applied to derive a new attitude. This attitude was shown to allow the HGA to point at Earth.

The next step was to assess UHF communication at this attitude. Figure 5 depicts the trajectory of Curiosity during EDL within the Odyssey UHF antenna cone with various events and their predicted times with Odyssey at the selected attitude.

This analysis indicated that communication with Curiosity would be maintained for several minutes after landing. This, then, was the final Odyssey attitude selected for EDL.

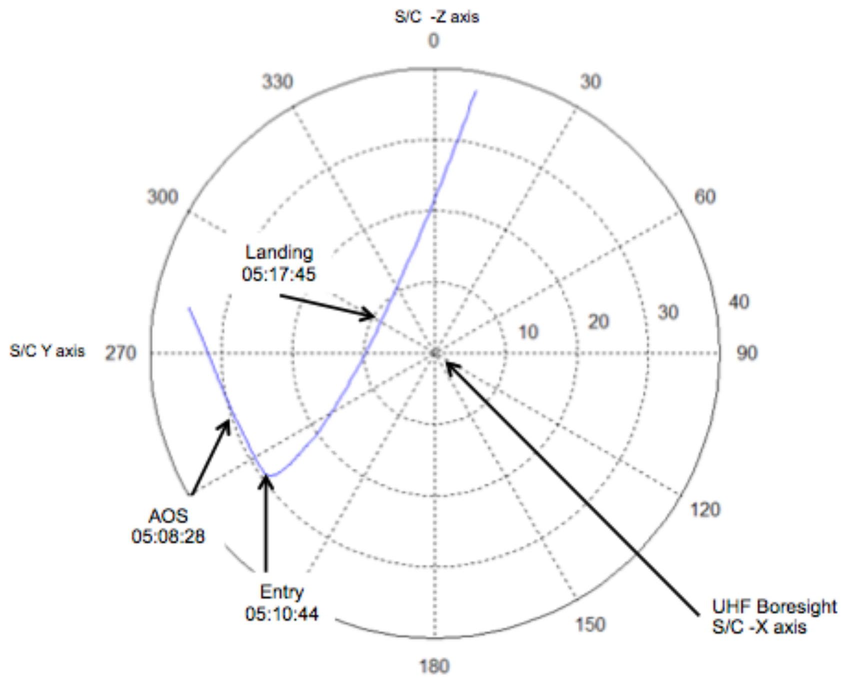

Figure 5 Curiosity Trajectory in Odyssey UHF Antenna Cone

Slew and EDL Hold Planning

Early in the planning process, the SCT expected to perform all attitude profiles under RWA control; all early planning was based on this expectation which was made invalid by later events. Odyssey RWA wheel speed of 518 rad/sec triggers entry into safe mode. In nominal operations, activities are planned so as to keep maximum wheel speeds in the 300 to 350 radians per second range. The original design of Odyssey sized the RWA array for momentum management while maintaining nominal attitude, described above, and performing slews of a few tens of degrees away from nominal attitude. Since the attitude selected for EDL operations was as much as 150 degrees away from nominal attitude, these operations constituted a major departure from the design envelope.

Initial simulations showed that, even with performing a desat to zero momentum immediately before the start of the first slew, RWA wheel speeds would exceed the safe mode entry point before completion of EDL profiles. The SCT found that by performing a special desat to bias the resulting momentum state after the initial slew to the EDL attitude while at inertial hold attitude, the hold and subsequent slew back to nominal nadir pointing attitude could be accomplished within RWA wheel speed limits.

Performing a desat requires first stowing the high gain antenna in a position to avoid thruster plume impingement. Thruster firings and reactive RWA commands are then issued to modify the momentum state, followed by repositioning the HGA for Earth communication. The vehicle attitude control system requires several minutes to reduce transients prior to re-establishing Earth communication lock up. All these activities had to be completed prior to the anticipated start of MSL communication. Pushing the start of the inertial hold back far enough to accomplish all these activities increased the magnitude of the slew required to arrive at the attitude at that time. To reduce this slew, the SCT decided to perform the slew roughly a full orbit prior to the start of EDL communications operations.

The final initial operations profile is depicted in Figure 6 and Figure 7 which show the spacecraft rotation rates and RWA wheel speeds with notations of operations being performed. Operations were tailored to keep wheel speeds below 250 radians per second, providing roughly 100% margin, because of increased uncertainty in the accuracy of the simulation's momentum modeling, given that unusually large maneuvers and an inertial hold at an attitude far from nominal were planned. The timing of the nominal, or background, desats in the days leading up to the EDL event was adjusted so that the last one occurred less than an orbit prior to the start of the initial slew to insure enough available momentum to perform that slew. The bias desat compensated for the anticipated momentum to be accumulated during the inertial hold and subsequent slew back to nadir.

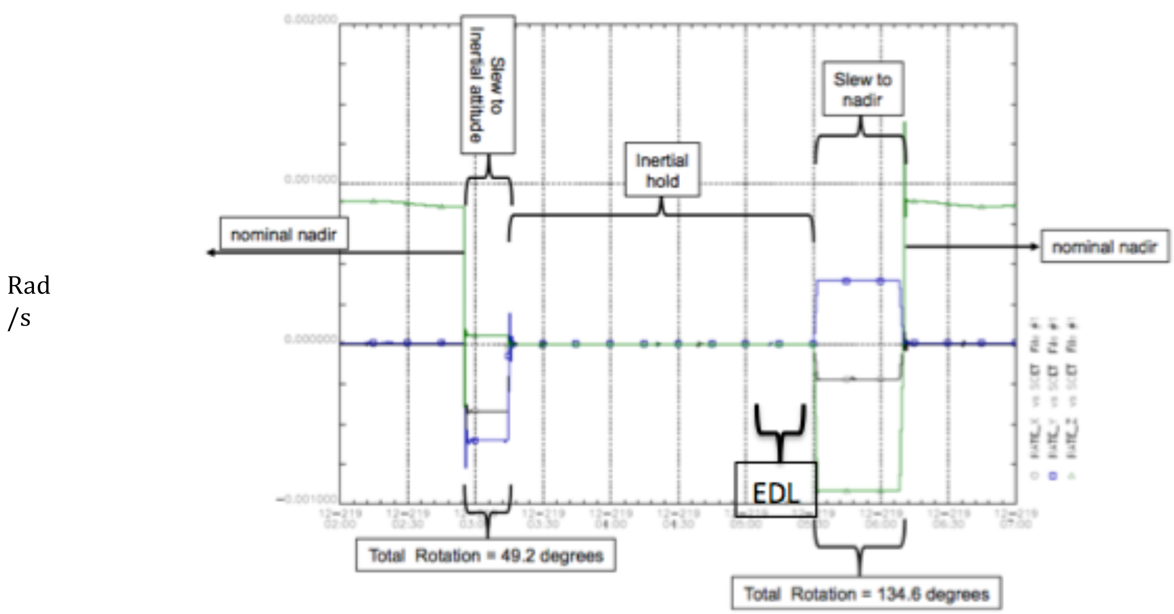

Figure 6 Spacecraft Rotation Rates during EDL Operations

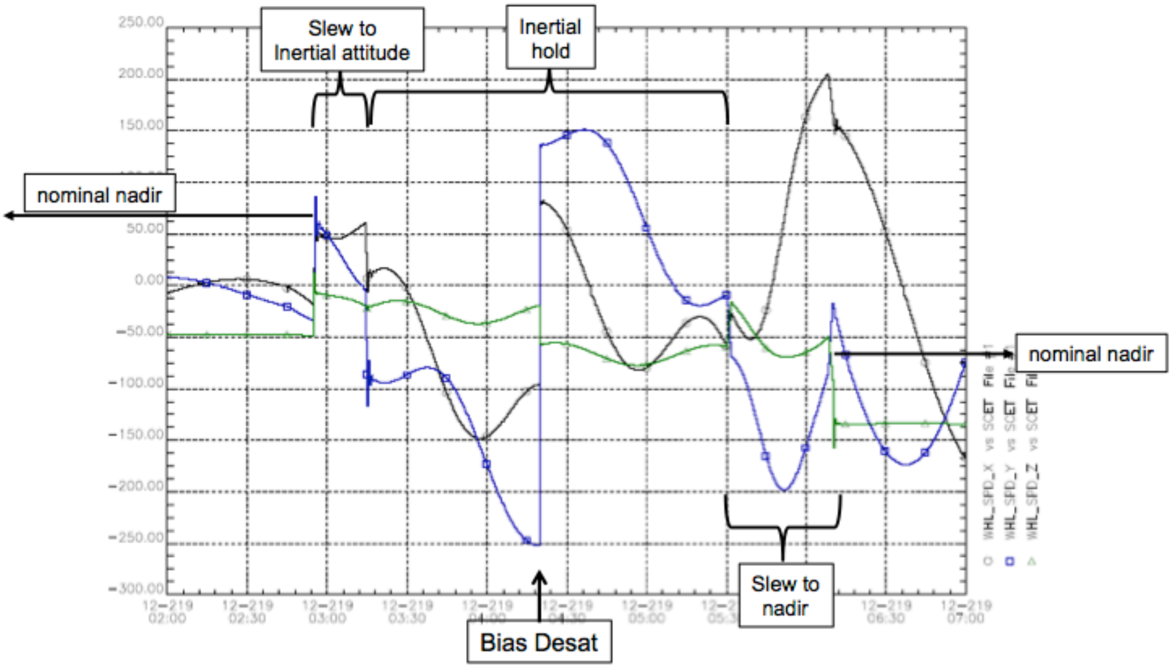

Figure 7 RWA Wheel Speeds during EDL Maneuvers

Normal practice in a paper such as the present would be to present the as flown data equivalent to that shown in Figure 6 and Figure 7 for comparison. Unfortunately, unforeseen events intervened and forced dramatic changes to the profiles planned.

RWA Anomaly, Safe Mode Entry

By late May, 2012, orbit phasing modification was progressing as planned, EDL attitude had been selected, slews to and from the EDL attitude had been planned as described, above, and numerous simulations of the operations had been performed, providing confidence in the attitude profile within the Odyssey community.

Then, on June 8, the number 1, or X axis, RWA experienced an anomaly causing the vehicle to enter safe mode. An apparent increase in bearing friction prevented the wheel from producing torque commanded by the control system which led to an attitude error exceeding the safe mode entry limit. Odyssey safe mode entry, after a series of autonomous system safing actions, commands inertial hold at an attitude providing power collection and Earth communication. In this attitude, momentum accumulation is much more rapid than nominal nadir pointing attitude; also, in safe mode desats are managed by simply allowing wheel speed to increase to the safe mode limit which, while in safe mode, merely triggers an emergency desat. As an intermediate step to full recovery, the spacecraft is

commanded back to nominal nadir following attitude by the SCT; momentum management is performed via desats every twelve hours until full recovery is achieved. The thrusting to effect these desats is random relative to its affect on orbit. The direct result of the safe mode thrusting was that the careful plan to manage desats to control Odyssey's phasing to support EDL was disrupted such that Odyssey would miss the targeted time/position by several minutes. Following recovery, an orbit trim maneuver was planned, requiring changing attitude to align thrusters with the velocity vector. A second safe mode entry occurred as a result of this operation which is described, below.

Skew Wheel Operational Impact

Because of the risk of another safe mode entry with continued use of RWA 1, the SCT decided to transition to RWA 4, the "skew" backup wheel. The RWA suite installation as nominally designed had three RWA's aligned with the three spacecraft coordinate frame axes and the fourth, backup or skew, RWA aligned equidistant, angularly, from each of the three coordinate frame axes. This arrangement is typical of many RWA installations and results in the angle between the skew RWA axis and each of the three axes being approximately 54.7 degrees. However, due to a manufacturing error, which was not discovered until after launch of Odyssey, the skew RWA axis was aligned 60 degrees away from the X and Y axes and 45 degrees away from the Z axis.

Use of a skew RWA in place of a faulty unit requires a larger wheel speed change than would have been required of the original RWA for a given momentum change in the axis of the faulty RWA. Also, because the skew RWA is not orthogonal to the other operational RWAs, the momentum or wheel speed of the skew RWA couples into the axes along which the other RWAs are aligned; the other RWAs must change their wheel speed to compensate for that of the skew RWA in addition to absorbing momentum in their respective axes. For the nominal installation the skew wheel must change its speed by a factor of 1.73 times what would have been required for the faulty RWA; the wheel speed required of the other two RWAs because of coupling is equal to that of the faulty RWA. Because of the misalignment of the skew RWA, the Odyssey skew RWA wheel speed must be twice that of the faulty X axis RWA; the coupling into the Y axis RWA is equal to that of the faulty X axis RWA while the Z axis coupling is 1.4 times that of the X axis.

First Orbit Trim Maneuver, Second Safe Mode Entry

Following the first safe mode entry and resulting orbit perturbations, the Odyssey Navigation team determined that the propulsive effect of desat operations no longer had enough authority to achieve Curiosity EDL positioning requirements. To correct this, a propulsive maneuver, or Orbit Trim Maneuver (OTM) was planned for and executed on July 11, 2012. Odyssey thruster alignment requires that the

spacecraft Z axis be aligned with the velocity vector for a phasing change OTM; this constitutes a ninety degree offset from the nominal operational attitude. The typical sequence of events is to slew to the burn attitude using RWA attitude control, transition to attitude control using thrusters during the OTM burn itself, transition back to RWA control at the conclusion of the OTM, wait for a specified time for transients to die out, then slew back to nominal attitude.

The SCT considered performing the slews to and from the OTM attitude under thruster control because of the lack of experience performing slews with the slew RWA active. However, because of the unpredictability of the contribution of the thruster firing during slewing on the net velocity change, the decision was made to perform the slews under RWA control.

Unfortunately, unexpectedly large transients at the end of thruster firing and the return to RWA control along with the coupling of the skew RWA caused the Z RWA wheel speed to exceed safe mode entry level and Odyssey entered safe mode once again. Just as with the safe mode entry of June 8, the effects of thrusting to manage momentum during recovery disrupted orbit phasing.

Second Orbit Trim Maneuver

Following the second safe mode entry and the attendant orbit phasing disruption, a second OTM was scheduled for July 24. This was just 12 days prior to MSL EDL. Again, the SCT decided to perform slews to and from the OTM attitude using RWA control to avoid unpredictable delta velocity resulting from using thruster control.

A number of operational changes were made to reduce the risk of another safe mode entry. The first major change was to stay under thruster control following the end of the OTM burn and allow a period of rate damping on thrusters prior to the transition to RWA control. The other major change was to change the commanded inertial hold attitude to the measured attitude at the same time as the transition to RWA control. These two changes eliminated any attitude error and minimized rate error at the transition to RWA control.

With these changes in place, the OTM was performed successfully. Navigation Team predictions again showed Odyssey meeting timing and phasing requirements.

EDL Operations

Following the RWA 1 anomaly, the SCT had begun replanning operations for the day of MSL EDL in parallel with the planning for the first and then the second OTM. Analysis showed that performing the attitude profile as originally planned

was extremely risky if not impossible. Figure 7 shows RWA wheel speeds assuming RWA 1 is operational. Use of the skew RWA dictates that its wheel speed will be twice that for RWA 1 for a given maneuver and coupling will add 1.4 times the RWA 1 wheel speed to that of the Z RWA; this would reduce wheel speed safety margins to virtually zero.

In light of this analysis, the SCT decided to perform the slews required to support EDL communication under thruster control. Since the slew to the EDL communication attitude occurred a matter of an hour or so prior to EDL, the delta velocity effects of thruster firings would have virtually no impact on Odyssey position at the time of EDL. However, maintaining reliable high bandwidth Odyssey to Earth communication required RWA attitude control. This required transition to RWA control after the slew to the communication attitude and then return to thruster control prior to the slew back to nominal nadir attitude.

These changes resulted in greatly simplified operations. The original plan called for completing the slew to the communication attitude roughly two hours before MSL EDL to allow for the bias desat and associated transient settling; the spacecraft momentum state at the end of all EDL operations was out of the nominal momentum management plan and would have to be corrected. By performing the slews under thruster control, the RWAs could be spun down under friction during the periods under thruster control, thus no bias desat was required after the first slew and the momentum state after all operations was essentially zero.

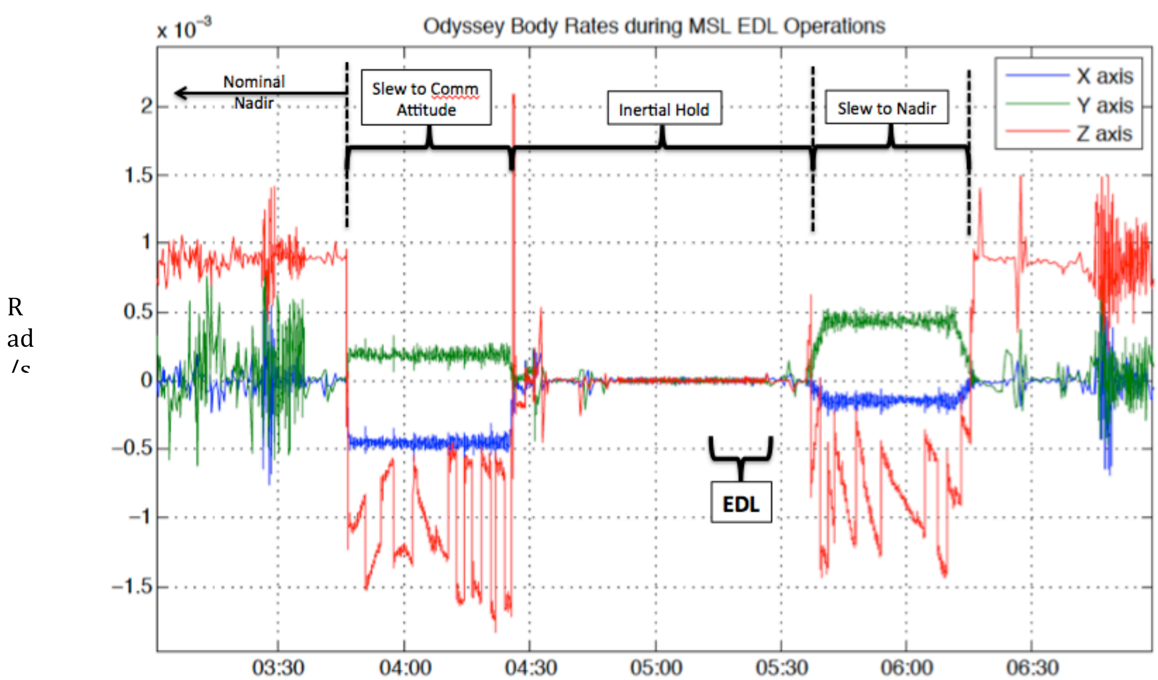

Figure 8 Body Rates during EDL Operations

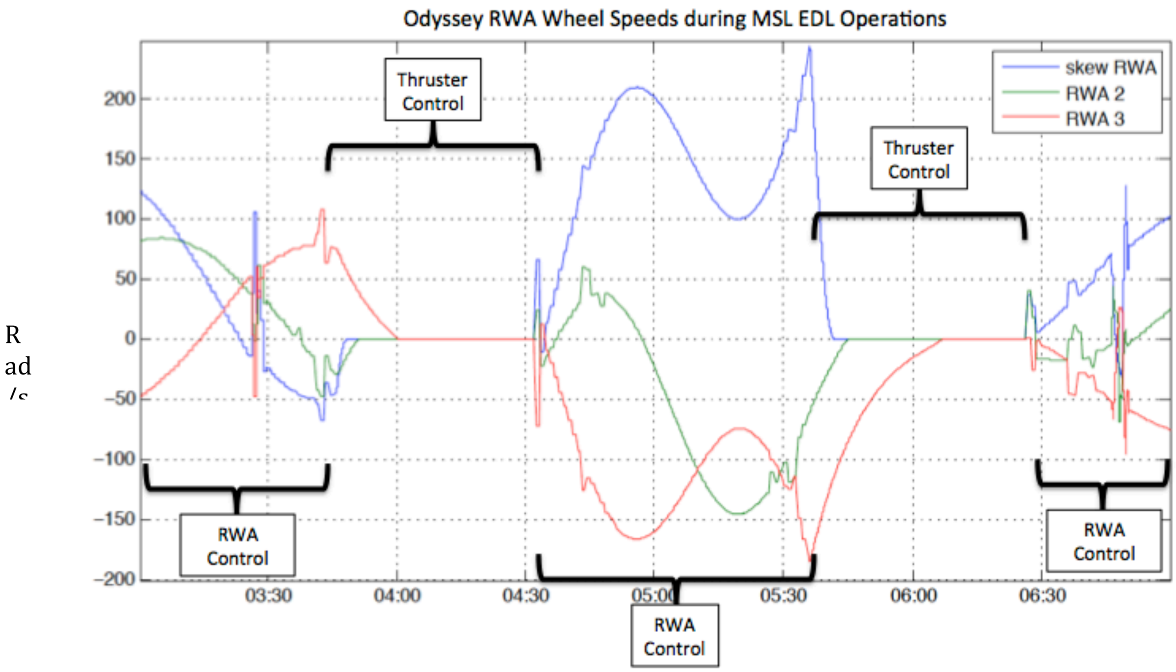

Figure 9 RWA Wheel Speeds during EDL Operations

Figure 8 shows bus rotational rates throughout the EDL operations. The slew to the communication attitude completed roughly forty minutes prior to MSL entry providing time for transient settling and establishing communication with Earth. Figure 9 depicts the RWA wheel speeds over the same time period. Allowing the RWAs to run down under friction during the periods of thruster control provided sufficient momentum capacity for operation on RWA control for the inertial hold period, lasting slightly more than an hour.

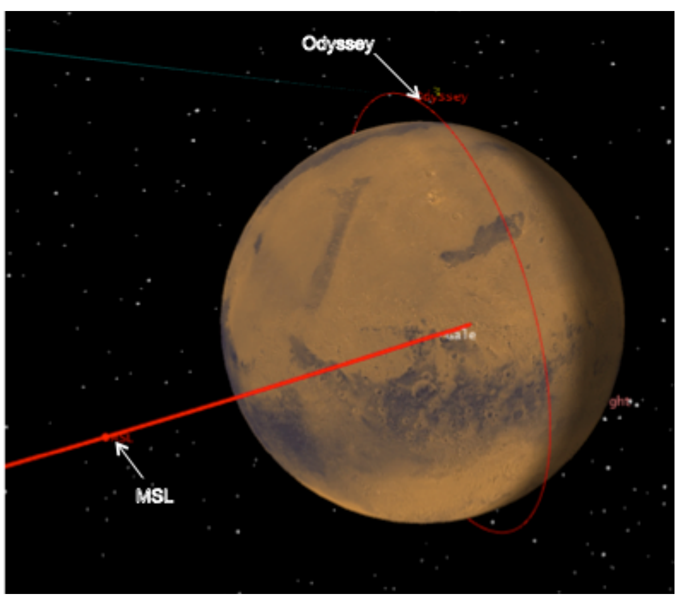

Figure 10 Odyssey and Curiosity Positions at Landing -18 minutes

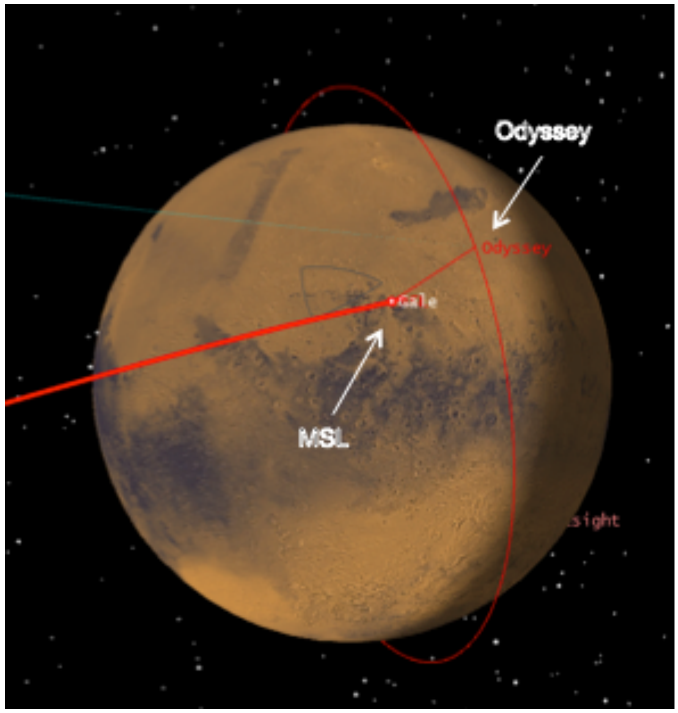

Figure 11 Odyssey and Curiosity Positions at Landing

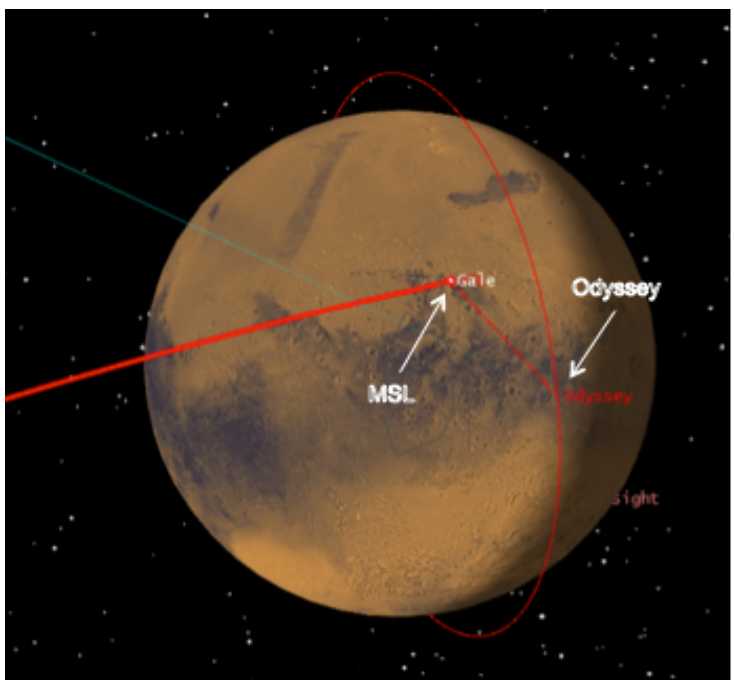

Figure 12 Odyssey and Curiosity Positions at Odyssey Set

Figure 10, Figure 11 and Figure 12 show the relative positions of MSL and Odyssey at various points in the EDL operation.

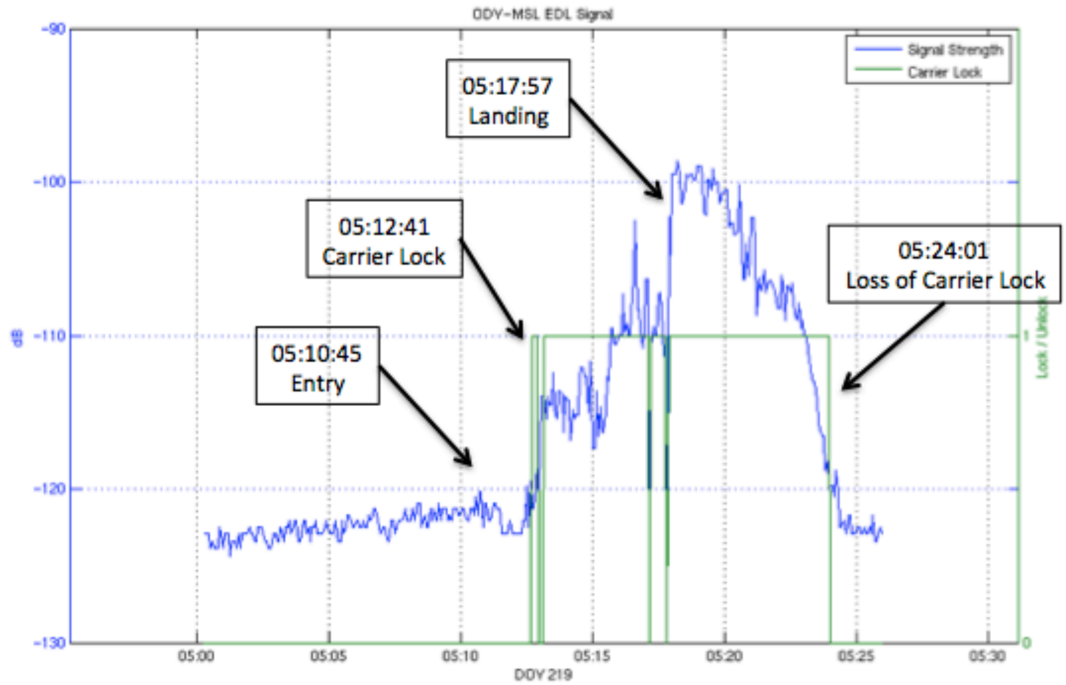

Figure 13 Odyssey - Curiosity UHF Signal

Figure 13 depicts UHF received signal strength during EDL. AOS was later than the time at which Curiosity entered the 30 degree Odyssey UHF antenna cone due to range and entry ionization attenuation. Bent pipe communication extended some five minutes beyond the requirement of landing plus one minute. This extra communication time allowed for immediate transmission of two images from Curiosity while on the surface; the first images would have been delayed until the next Odyssey pass occurring roughly two hours later.

CONCLUSION

The Odyssey Mars Orbiter successfully provided real time communication relay to Earth from The Mars Science Laboratory, Curiosity, during the Entry, Descent and Landing phase of its mission. The Odyssey Team was faced with several challenges during preparations for the event, including orbit modification and unusual attitude maneuvers, complicated by an RWA anomaly and two safe mode entries in the weeks leading up to Curiosity arrival at Mars.

ACKNOWLEDGMENTS

Needless to say, achieving relay communication with Curiosity during EDL through Odyssey was a team effort. The authors wish to acknowledge the contributions of Gaylon McSmith, JPL Odyssey Project Manager (now retired),

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